GROWTH PERFORMANCE, CARCASS COMPOSITION, AND PORK FAT QUALITY OF GROWING-FINISHING PIGS FED DISTILLERS DRIED GRAINS WITH SOLUBLES (DDGS) WITH VARIABLE OIL AND ENERGY CONTENT, AND PREDICTION OF METABOLIZABLE AND NET ENERGY

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Dedication

I would like to dedicate this thesis to my parents Yongping Wang and Bian Wu, and to my girlfriend Jingwen Liao. This two-year graduate study would not have been possible without their love, encouragement, and support.

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CHAPTER 1

Introduction and literature review

Introduction

Corn distillers dried grains with solubles (DDGS) are a co-product resulting from fermentation of starch present in corn or other grains to ethanol for beverages or biofuels (Cromwell et al., 1993). With increasing demand for biofuels and the subsequent rapid expansion of ethanol production in the U.S., DDGS production has increased from 2.3 million metric tons in 1999 to 35.5 million metric tons in 2013 (RFA, 2014). Almost all of the DDGS produced in the U.S. has been used as animal feed, with the majority used in diets for dairy (53.5%) and beef (33.9%) cattle, with lesser amounts being fed to swine (7.3%) and poultry (5.3%; Wisner, 2013). Furthermore, a significant quantity of DDGS is exported. Wisner (2013) estimated that of the 39.9 million metric tons of DDGS produced in 2014, 25% of this amount was exported primarily to Asian countries and Mexico.

Traditionally, pork production systems in the Midwest region of the U.S. have predominantly relied on corn and soybean meal as the primary energy and amino acid (**AA**) sources, respectively, in commercial diets. However, high feed ingredient prices around the world have created a need to search for more cost effective alternative feed ingredients to minimize feed cost. High concentrations of energy, protein, and digestible phosphorus have made DDGS an attractive ingredient to partially replace corn and soybean meal in animal feed (USGC, 2012), and the economic advantage of adding DDGS to diets has resulted in increased use of DDGS in swine diets.

However, one of the biggest concerns related to using DDGS in swine diets is the variation in chemical composition and energy content among sources, as well as variation among batches within the same ethanol plant. This variation in energy and nutrient content makes accurate and precise diet formulation difficult. Historically, traditional sources of DDGS contained greater than 10% oil, with metabolizable energy (**ME**) content comparable to corn (Stein and Shurson, 2009). In recent years, however, more than 90% of U.S. ethanol plants have adopted oil extraction technologies and produce DDGS with oil content varying between 5 to 12% (Kerr et al., 2013). Oil extraction further increases the inherent variability of nutrient content, and has caused concerns regarding the impact of reduced-oil content on energy concentration and feeding value of DDGS. As a result, prediction equations based on analyzed chemical composition of DDGS have been developed to estimate digestible (**DE**), ME, and net energy (**NE**) content for DDGS sources (Noblet and Perez, 1993; Noblet 1994b; Pedersen et al., 2007; Anderson et al., 2012; Kerr et al., 2013; Graham et al., 2014b), but these equations have not been validated in swine growth performance studies. Therefore, chapter 2 and 3 present results from two experiments on the effects of oil concentration and predicted energy content of DDGS on growth performance and carcass composition of growing-finishing pigs.

Moreover, the negative impact of including DDGS in growing-finishing diets on pork fat quality has been widely reported (Xu et al., 2010a; Cromwell et al., 2011; McClelland et al., 2012; Lee et al., 2013; Davis et al., 2015). High concentrations of unsaturated fatty acids (**FA**) contained in corn oil present in DDGS often causes an unacceptable iodine value (**IV**) and a reduction in firmness of pork fat. This issue is

especially noticeable when more than 20% of high oil (>10% crude fat) DDGS is included in growing-finishing pig diets (Stein and Shurson, 2009). Consequently, a potential benefit of feeding reduced-oil DDGS is improved pork fat quality due to reduced intake of unsaturated FA by growing-finishing pigs. Chapter 2 and 4 of this thesis provide data showing the magnitude of improvement in pork fat quality from feeding diets containing DDGS sources with reduced concentrations of ether extract (**EE**). These FA composition data were also used to evaluate published IV prediction equations for carcass fat depots, which was described in chapter 4.

Finally, wheat middlings (**WM**) are a by-product from flour milling, and contain greater crude protein (**CP**) and fiber content, but less ME and NE relative to corn. Wheat middlings are produced in significant quantities in the U.S., and have also been used as a cost competitive, alternative ingredient to partially replace corn and soybean meal in growing-finishing swine diets. However, limited information exists regarding the growth and carcass responses of growing-finishing pigs fed diets containing WM and reduced-oil DDGS. Therefore, we conducted an experiment to measure the impact of feeding WM and reduced-oil DDGS when formulating diets on a NE basis, on growth performance and carcass composition of growing-finishing pigs in chapter 5.

Corn distillers dried grains with solubles

Production of DDGS in the U.S. ethanol industry

The American Association of Feed Control Officials have defined DDGS as "the product obtained after removal of ethyl alcohol by distillation from the yeast fermentation of a grain or grain mixture by condensing and drying at least three quarters of the solids of the resultant whole stillage by methods employed in the grain distilling industry"

(AAFCO, 1995). There are 2 main processes for utilizing starch to produce ethanol and co-products, which include dry-grind and wet milling.

The dry-grind process (Figure 1.1) entails several key steps, including corn grinding, cooking, liquefaction, saccharification, fermentation, distillation, ethanol storage and loadout, centrifugation, and co-product drying and loadout (Rosentrater and Liu, 2011). Briefly, the initial step of processing corn to produce ethanol is to reduce the particle size of corn by grinding it in a hammer mill, followed by mixing ground corn with water, recycled thin stillage (also known as backset), and enzymes (amylase) to produce a slurry. Cooking is then used to hydrolyze starch into glucose. Yeast (*Saccharomyces cerevisiae*) is added to ferment glucose to ethanol, which is removed by distillation. The mixture of remaining non-fermentables (whole stillage) is separated into liquid (thin stillage) and coarse solids (wet cake) through centrifugation. Oil extraction processes are used in many ethanol plants, which occur by centrifugation of thin stillage after fermentation and distillation, and before drying, to produce DDGS. Next, thin stillage (5.0 to 7.7% DM) goes through an evaporator to produce condensed distillers soblubles (approximately 30% DM), which is then mixed with wet cake and dried to produce DDGS (USGC, 2012). Drying is one of the most essential processes in DDGS manufacturing, and is conducted typically using either rotary drum dryers or ring dryers at a high temperatures (over 500°C at the dryer inlet and over 100°C at the dryer discharge) for approximately 10 to 20 min. Dry-grind ethanol plants produce approximately 36 liters of ethanol, 32 kg of DDGS, and 32 kg of carbon dioxide from each 100 kg of corn that is fermented (USGC, 2012). Wet cake can also be sold directly as distillers wet grains (**DWG**; 35 to 50% DM), which is used in feedlot cattle diets with

inclusion levels ranging from 20 to 40% of diet DM (Erickson et al., 2005). O'Brien and Woolverton (2010) estimated that, during 2009, about 44% of by-products produced in dry-milling plants were in the form of DWG, followed by DDGS representing about 38.6% of total co-product production.

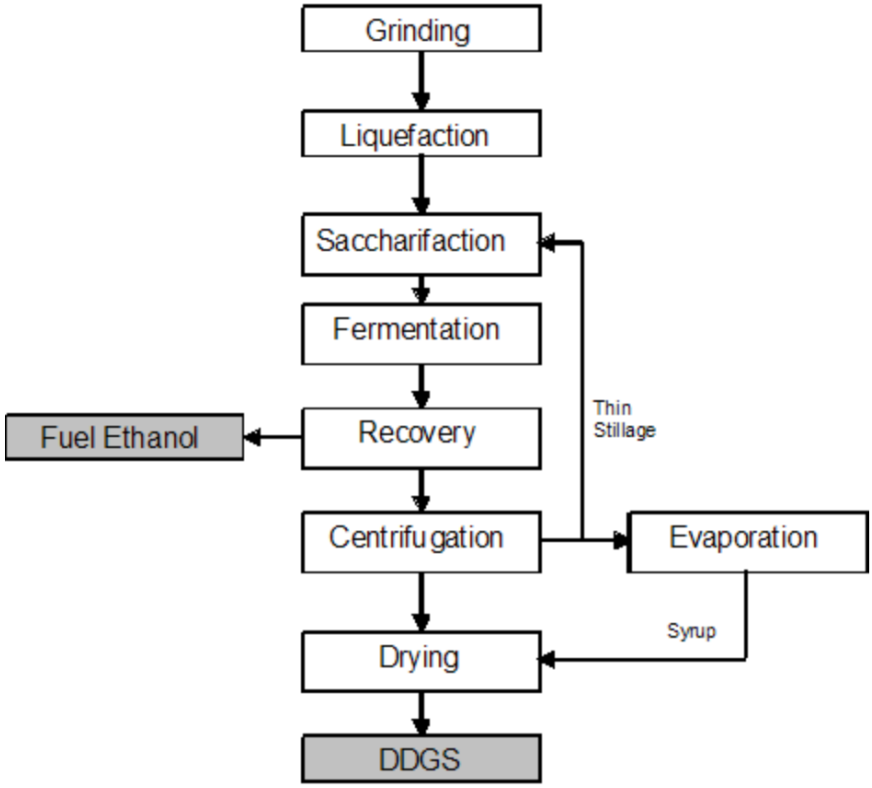

Figure 1.1. Simplified flow chart of ethanol and DDGS production in dry-grind ethanol plants. Adapted from McAloon et al. (2000).

Back-end oil extraction technology has been implemented by more than 90% of the ethanol plants because of the high financial benefits from marketing distiller's corn oil into the biodiesel and animal feed markets. Currently, oil extraction technology consists of 2 types of systems (Figure 1.2). The "Step 1" extraction method is the most common process used in ethanol plants, and involves extracting corn oil by centrifugation from the thin stillage after it is removed from the whole stillage (CEPA, 2011). Thin

stillage contains approximately 30% of the total oil content present in corn, which is mostly removed during the "Step 1" extraction process. Some ethanol plants have also adopted the "Step 2" extraction method to capture an additional 30% of corn oil that is present in the whole stillage prior to the centrifuge separation of the wet grains and thin stillage (CEPA, 2011). Since more than 40% of corn oil is trapped in the wet cake, "Step 2" extraction requires the use of an extra washing technique to liberate this oil from the wet cake, which can then be removed in the "Step 1" process. The combination of using "Step 1" and "Step 2" methods can extract 60 to 70% of the corn oil during ethanol production, which equals to about 6 to 7 liters of corn oil per 100 liters of ethanol production (CEPA, 2011).

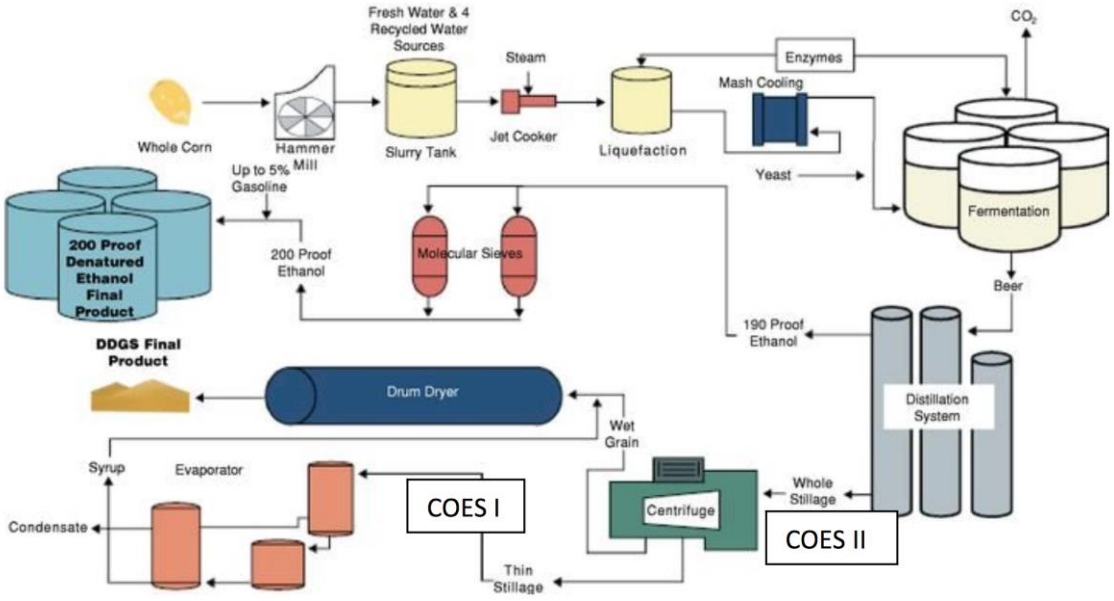

Figure 1.2. Corn oil extraction system (COES) in dry-grind ethanol plants. Adapted from CEPA (2000).

Wet milling is a process that separates and purifies fractions of the corn kernel (starch, oil, protein, and fiber) to produce numerous products, some of which are intended for ethanol production, food products, and animal feed uses (Stalker et al., 2010). A brief

description of wet milling processes depicted by USGC (2012) is presented in Figure 1.3. After initial cleaning, corn kernels are soaked in a solution with SO_2 (0.1 - 0.2%) and lactic acid under a controlled temperature (48 - 50°C) and time (35 - 50 hours). When the steeping is complete, corn germ is separated from the corn kernel by milling using hydrocyclones, and the remaining germ fractions are sold wet or dry as corn germ meal. Once the germ is removed, the remaining endosperm fraction is purified to remove starch and protein extracts (gluten), and the leftover fractions (corn bran and spent germ) is mixed with steep water to produce corn gluten feed. Meanwhile, oil is extracted from the germ to produce corn oil. Next, the gluten extracts are separated by high-speed centrifugation into light proteins and starch that are further processed to produce corn gluten meal and pure starch, respectively. Purified starch can then be dried, fermented to produce ethanol, or refined to produce corn syrup. If the wet milling plant ferments starch into ethanol, a portion of the steep water (steep liquor) is added to fermentation vats to provide nutrients for yeast. The procedure used to produce ethanol is similar to that previously described for dry-grind ethanol plants. Wet milling requires a large capital investment and therefore, contributes to a smaller proportion (40%) of the total ethanol production in the U.S. compared with dry-grind plants (60%; Urriola, 2007).

It is important to note that corn by-products from wet milling plants have different nutritional profiles compared with corn DDGS from dry-grind ethanol plants. Corn germ meal (9.9% moisture, 23.3% CP, 2.1% EE, and 44.5% NDF; NRC, 2012) is made from the remaining germ portion of the corn kernel and other grain fragments after cyclone milling and oil extraction, resulting in medium protein and high fiber concentrations. Corn germ meal has an AA balance that makes it valuable in poultry and swine diets

(USGC, 2012). Corn gluten feed (12.9% moisture, 17.4% CP, 4.2% EE, and 27.5% NDF) is the product of mixing residual germ after oil extraction, corn bran, and steep liquor. Corn gluten feed is also a medium protein ingredient and is primarily used in dairy and beef cattle rations (USGC, 2012). Corn gluten meal (10.0% moisture, 58.3% CP, 4.7% EE, and 1.6% NDF) is a high protein concentrate resulting from removing the starch fraction from the fiber-free endosperm. Corn gluten meal is a good source of protein, energy, and pigments for livestock species (including fish), and it is also valued in pet food due to its high protein digestibility (RFA, 2008).

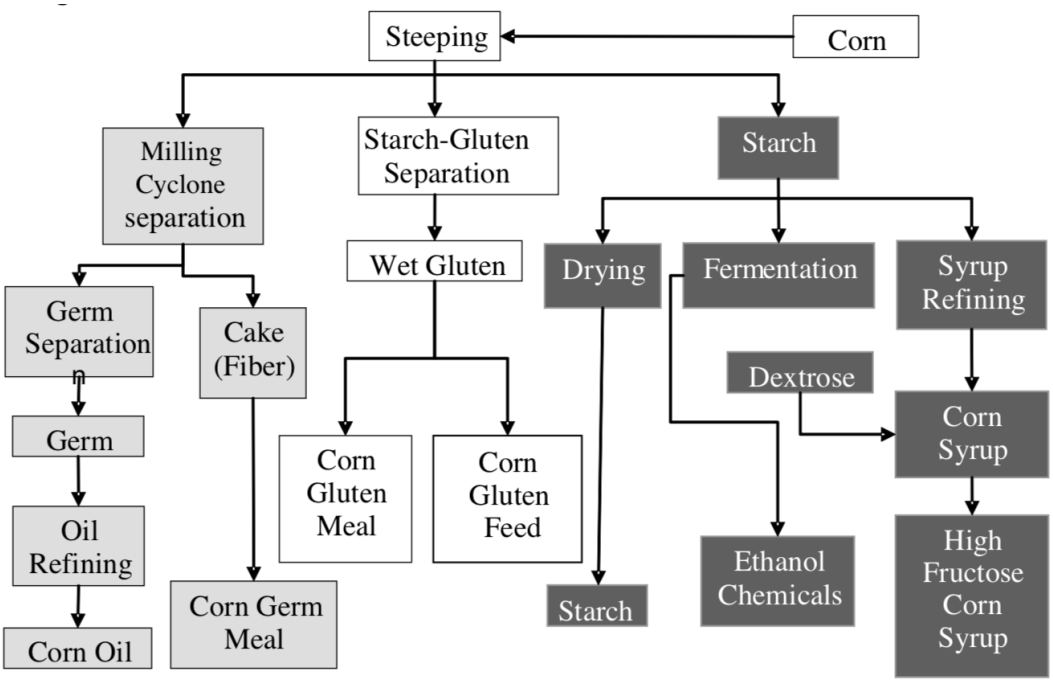

Figure 1.3. Simplified flow chart of wet milling process. Adapted from Erickson et al. (2005).

Nutrient composition and variation among DDGS sources

The nutrient composition of DDGS is partially a result of the nutrient composition of the grains used to produce ethanol (Stein and Shurson, 2009). In general, corn contains approximately 62.6% starch, 8.2% crude protein (**CP**), 9.1% neutral detergent fiber (**NDF**), and 3.5% corn oil (NRC, 2012; as-fed basis). After conversion of most of the

starch from corn into ethanol, concentrations of the remaining nutrients increase about three-fold in corn DDGS (Spiehs et al., 2002). Accordingly, traditional (high-oil) corn DDGS contains about 6.7% starch, 27.3% CP, 32.5% NDF, and 10.4% EE content (NRC, 2012; as-fed basis). With oil extraction, medium- and low-oil DDGS sources have slightly increased starch content (9.6 and 10.0%, respectively), similar concentrations of CP (27.4 and 27.9%, respectively) and NDF (30.5 and 33.7%, respectively), and decreased EE content (8.9 and 3.6%, respectively) compared with traditional high-oil DDGS (NRC, 2012; as-fed basis). As a result of the relatively high concentration of crude fat, and contributions from fiber, protein, and residual starch, DDGS is a good source of energy for both ruminant and non-ruminant animals (USGC, 2012).

Energy and nutritional value of DDGS varies among species. Due to their ability to utilize fiber through microbial fermentation in the rumen, net energy of DDGS is about 20% greater than that of corn in finishing beef cattle diets (Ham et al., 1994). In addition, the fermentation and drying processes during the production of DDGS reduces the proportion of the protein in corn that is readily degradable by ruminal microbes, and therefore, rumen undegradable protein content is proportionally increased. As a result, DDGS has been successfully used at dietary inclusion rates as high as 40% and 20% of diets for finishing beef and dairy cattle, respectively, in the U.S. (USGC, 2012). When fed to poultry, traditional high-oil corn DDGS contains about 85% of ME value of corn. As a result, it has been successfully included at lower dietary inclusion rates for broilers (5 to 8% in starter diets, 12 to 15% in growing-finishing diets), layers, ducks, and turkeys. However, higher dietary inclusion rates can be achieved if diets are formulated on a digestible AA basis with dietary energy adjustments (USGC, 2012).

In swine diets, the National Research Council (NRC, 2012) nutrient composition tables indicate that traditional DDGS with oil content greater than 6% should have an ME content comparable to corn. However, NE content of DDGS is about 400 kcal/kg less in medium- (> 6 and < 9%) or high- (> 10%) oil sources, and about 800 kcal/kg less in low- (< 4%) oil sources compared with that of corn (Table 1.1). However, it is important to note that the published ME values for the medium- and low-oil DDGS were based on only a few published values, and NE values for all DDGS sources were calculated using published equations developed based on complete diets. Therefore, the accuracy of these energy values is questionable. Variation in energy content has been commonly observed among DDGS sources (Pedersen et al., 2007; Anderson et al., 2012; Kerr et al., 2013). Numerous studies have been conducted to determine the ME and NE values of DDGS sources and to develop prediction equations to manage this variation (discussed in a later section of this chapter).

Distillers dried grains with solubles is high in dietary fiber (defined as the sum of non-starch polysaccharides and lignin). Fiber content is less digestible and has a negative impact on digestibility of other nutrients, such as crude protein and fat (Noblet and van Milgen, 2004). Generally, NDF content is about 3 times more concentrated in DDGS compared with corn, and it is highly variable among sources with an averaged CV of 13.0% (Table 1.1). Urriola et al. (2010) measured the fiber content of more than 24 sources of corn DDGS and showed that the concentration of TDF varied from 18.6 to 31.4% among the 10 sources of DDGS used in experiment 1, and crude fiber (6.1 to 7.4%), ADF (9.7 to 12.9%), NDF (37.4 to 44.4%), and TDF (28.7 to 34.9%) also varied among the 8 DDGS sources in experiment 2 (Urriola et al., 2010).

Crude protein concentration in DDGS is typically greater than 30% on a DM basis, which is significantly greater than corn (9.3%; Table 1.1). However, the relative proportions of AA in DDGS are not substantially different from those in corn because they are not affected during the fermentation process. However, the concentrations of each AA are about 3-fold greater than in corn. In particular, lysine level (0.88% averaged over 3 classes of DDGS in Table 1.1) is low relative to CP content in DDGS. Therefore, the protein quality of DDGS is considered poor relative to the AA requirement of pigs. Feeding diets containing an unbalanced AA profile increases nitrogen excretion and expenditure of metabolic energy for nitrogen removal, resulting in less energy available to pigs for productive purposes (Spiehs et al., 2002). Digestibilities of AA in DDGS are generally 10 percentage units less compared with corn (Stein and Shurson, 2009). Reduction in AA digestibility is mainly a result of Maillard reactions, which are a group of reactions that occur during the drying process of DDGS. The Maillard reactions involve a complex series of reactions among reducing sugars and AA (also other carbohydrate and amine groups) leading to the formation of a variety of products, such as Amadori compounds and pre-melanoidins, which are undigestible to pigs (Urriola, 2007). Moreover, lysine is particularly susceptible to undergo Maillard reactions because of its free amino group (Almeida et al., 2013). Studies (Spiehs et al., 2002; Stein et al., 2006; Pahm et al., 2008) have reported high variability in lysine digestibility in DDGS, but digestibilities of other AA are within the normal range of variation observed in other feed ingredients. Since DDGS sources that have low lysine digestibility often have low lysine content, the lysine to CP ratio can be used to estimate the relative lysine digestibility among DDGS sources (Stein, 2007). Other methods have also been evaluated for use in

predicting AA digestibility in DDGS. Fastinger and Mahan (2006) used colorimetric measurement with Minolta or HunterLab spectrophotometers to assess lysine digestibility of 5 sources of DDGS, and showed that darker colored DDGS had lower total lysine content and reduced AA digestibility compared to lighter colored DDGS sources. However, Urriola et al. (2013) showed that using colorimetric measurements poorly predicted digestibility of AA based on the concentration of standardized ileal digestible (**SID**) AA of 34 DDGS sources, and that using optical density and front face fluorescence methods provided better estimation of SID AA concentrations. Most recently, Almeida et al. (2013) determined the AA digestibility of heat damaged DDGS and developed regression equations to predict SID AA content of DDGS sources based on analyzed chemical composition (e.g. AA profile and acid detergent insoluble nitrogen). The KOH test has been developed to measure protein solubility in a 0.2% solution of KOH, which can be an indicator of AA digestibility in pigs (Gabert et al., 2001). Commercial assessments like AMINORED® (Evonik Industries, Essen, Germany) and IDEA™ (Novus International, St. Louis, Missouri) are also available to provide a rapid evaluation of AA digestibility in heat-processed feed ingredients.

Corn contains approximately 0.29% P (primarily as phytate; Table 1.1), but the biological availability of phytate for pigs is poor. However, phytate can be degraded by phytase produced by yeast during the fermentation process (Liu and Han, 2011), which significantly improves the bioavailability of P in DDGS. Bioavailability of P in feed ingredients can be directly estimated using a slope ratio method (Cromwell, 1992). This method involves comparing bone-breaking strength, bone ash, or P in bone ash of pigs fed graded levels of the test ingredient and a standard P source, which is both labor

intensive and costly. An alternate assessment of available P in an ingredient is to determine the P digestibility. The NRC (2012) suggests that P in DDGS (65%) has a markedly improved standardized total tract digestibility (**STTD**) relative to corn (34%). Pedersen et al. (2007) also reported that ATTD of P in 10 selected DDGS samples was greater than corn (59.1 vs. 19.3%, respectively). Therefore, when DDGS is included in swine diets, the need for supplemental inorganic P (mono- or dicalcium phosphate) is reduced when formulating on a STTD P basis.

Table 1.1. Chemical composition of corn distillers dried grains with solubles (DDGS) and corn from NRC (2012)[1] on a DM basis

	DDGS			
Item	> 10% oil	> 6 and < 9% oil	< 4% oil	Corn
No. of samples	12 to 81	4 to 13	1 to 2	37 to 163
DM, %	89.3 (2.1)	89.4 (1.7)	89.3 (2.5)	88.3 (2.7)
Crude protein, %	30.6 (5.6)	30.6 (7.3)	31.2 (17.0)	9.3 (11.3)
Ether extract, %	11.7 (9.9)	10.0 (5.2)	4.0 (17.4)	3.9 (22.4)
Crude fiber, %	7.9 (17.6)	10.0 (15.5)	6.9	2.2 (30.8)
ADF, %	13.2	13.5 (20.5)	18.9	3.3 (28.8)
NDF, %	36.4 (16.7)	34.1 (18.6)	37.8 (3.6)	10.3 (21.6)
Starch, %	7.5 (25.3)	10.8 (30.6)	11.2	70.8 (7.4)
Ca, %	0.13 (158.3)	0.09 (87.5)	0.06	0.02 (50.0)
P, %	0.82 (13.7)	0.67 (33.3)	0.85	0.29 (19.2)
Essential AA, %				
Arg	1.30 (14.7)	1.38 (13.0)	1.47	0.42 (13.5)
His	0.79 (9.9)	0.83 (10.8)	0.92	0.27 (20.8)
Ile	1.14 (8.8)	1.19 (8.5)	1.14 (27.5)	0.32 (21.4)
Leu	3.50 (14.7)	3.64 (13.5)	4.08	1.09 (15.6)
Lys	0.86 (15.6)	1.01 (14.4)	0.76 (41.2)	0.28 (16.0)
Met	0.62 (16.4)	0.64 (19.3)	0.56 (24.0)	0.20 (16.7)
Phe	1.50 (7.5)	1.53 (11.7)	1.89	0.44 (12.8)
Phe	1.50 (7.5)	1.53 (11.7)	1.89	0.44 (12.8)
Thr	1.11 (8.1)	1.11 (6.1)	1.09 (18.6)	0.32 (14.3)
Trp	0.24 (14.3)	0.22 (15.0)	0.20 (5.6)	0.07 (16.7)
Val	1.51 (8.9)	1.56 (8.6)	1.50 (20.9)	0.43 (13.2)
Swine ME, kcal/kg	3,845	3,801	3,476	3,844
Swine NE, kcal/kg	2,669	2,622	2,251	3,026

[1] Values expressed on 100% DM basis. Coefficient of variation (%) presented in parenthesis when available.

Factors that affect nutrient composition of DDGS

Variation in chemical composition of DDGS occurs not only among ethanol plants, but also among fermentation batches (Belyea et al., 2010). Causes of this variation are due to several factors including characteristics of raw materials used, processing factors used during production, and analytical methodology (Olentine, 1986; Belyea et al., 2010; Liu and Rosentrater, 2011). Olentine (1986) listed numerous variables in the raw materials that contribute to the variation in nutrient composition, including corn variety and factors that affect corn quality, such as soil conditions, fertilizer utilization, weather, as well as production and harvesting methods. In addition, physical properties of ground corn can also affect the nutrient composition of DDGS. For instance, reduction of particle size involves disruption of the outer seed coat and exposure of the endosperm of the grain (Amerah et al., 2007). Smaller particle size and greater surface area of ground corn facilitates gelatinization of starch granules and increases the amount of fermentable sugars formed (Naidu et al., 2007). However, if particles are too fine, centrifuge efficiency is reduced, leading to an increased amount of solids in thin stillage and thus, greater energy cost for evaporation of thin stillage (Naidu et al., 2007). Therefore, particle size of grain markedly affects ethanol yield and the concentrations of residual nutrients (e.g. starch) in co-products.

Liu and Rosentrater (2011) summarized several processing factors that are associated with significant changes in chemical composition and nutritional properties of DDGS, which include: 1) modification of production methods to remove one or more non-fermentable chemical components (e.g. corn oil); 2) processing parameters, such as degree of fermentation, ratio of blending the grains fraction with distiller's solubles, and

duration and temperature of drying process, which are determinants of concentration and digestibility of protein and starch; and 3) yeast used during fermentation which affects fermentation efficiency and the AA composition of protein remaining in DDGS.

Accuracy of laboratory measurement and variation of analytical methods are other important sources of variation in chemical composition among DDGS sources. For example, researchers have shown that analytical variability existed among and within laboratories for nutrient composition of corn and soybean meal sources (Cromwell et al., 1999), as well as wheat middlings (Cromwell et al., 2000), and that analytical variability might be as great, or even greater than the variability among sources of ingredients. In 2007, American Feed Industry Association (AFIA) conducted an extensive evaluation of the accuracy and precision of various analytical methods for moisture, CP, crude fat, and crude fiber of DDGS among 23 laboratories. Both intra-laboratory and inter-laboratory variability were determined, and different results were obtained using various analytical procedures. To solve this issue, standardized protocols were developed by AFIA (2007) for voluntary use in analyzing the chemical compounds in DDGS.

Impact of reduced oil content on the feeding value of DDGS for swine

With removal of corn oil, DDGS yield is reduced by approximately 9.4% (USGC, 2012), and chemical and physical properties of the resulting DDGS are substantially altered. Saunders and Rosentrater (2009) evaluated 42 sources of commercially-processed, solvent extracted DDGS and compared their physical and chemical characteristics with unmodified DDGS sources. They observed that sources of low-oil DDGS tended to have reduced water activity (longer potential shelf-life), less angle of repose (increased flowability), but unchanged bulk density. In addition, removal of a

portion of the oil consequently resulted in removal of some of the lipid-soluble pigments (e.g. carotenoids) causing a lighter color of DDGS. Furthermore, the CP (34.0%) and crude fiber (8.4%) concentrations in low-oil DDGS were increased compared with traditional high-oil DDGS sources. However, the increase of nutrient content may not be proportional to the reduction of oil in DDGS sources because of inherent variability in raw material and technologies utilized by ethanol plants. For example, in research conducted by Kerr et al. (2013), 3 sources of reduced-oil DDGS with varied EE content (4.9, 5.6, and 7.5%) had similar amount of CP (31.2, 30.6, and 30.8%, respectively) and TDF (35.6, 36.1, 36.0%, respectively) compared with a traditional high-oil DDGS source (10.8% EE, 28.9% CP, and 33.8% TDF).

Because oil contains 2.25 times more energy than carbohydrates and protein, oil extraction from DDGS has increased variability in energy and nutrient content, and consequently, the feeding value of DDGS. First, oil concentration directly affects the gross energy (GE) concentration of DDGS. Anderson et al. (2012) reported a decreased GE content (5,076 kcal/kg DM) of a low-oil (3.2%) DDGS source compared with the average GE content (5,420 kcal/kg DM) among 6 conventional high-oil (10.2 to 12.1%) DDGS sources. Graham et al. (2014b) also observed that GE content of 4 DDGS sources increased from 4,706 to 5,262 kcal/kg DM as oil content increased from 5.4% to 12.1%. Based on the analysis of 15 sources of DDGS, Kerr et al. (2013) suggested that a decrease of 46 kcal GE/kg could be expected with each 1% reduction in EE content of DDGS (GE, kcal/kg = 4,553 + 45.63 × EE, %; $R^2 = 0.87$, $P < 0.01$). Furthermore, wide ranges of DE (3,100 to 3,868 kcal/kg DM) and ME (2,858 to 3,650 kcal/kg DM) content have been reported for DDGS sources with reduced EE content (4.56 to 7.45%; DM

basis; Jacela et al., 2011; Anderson et al., 2012; Kerr et al., 2013). However, EE content appears to be a poor predictor of DE and ME content of DDGS for swine, and measures of dietary fiber (ADF or TDF) are important factors in determining DE and ME content of DDGS (Kerr et al., 2013).

In addition to the energy values, digestibility of other nutrients can be affected by extracting oil from DDGS. Curry et al. (2014) showed that 2 samples of reduced-oil DDGS (8.43 and 7.89% acid hydrolyzed EE; DM basis) obtained from the same ethanol plant had decreased SID values for most AA relative to conventional DDGS (12.66% acid hydrolyzed EE), and that the lower digestibility in reduced-oil DDGS could not be overcome by adding corn oil to the diets. Likewise, Gutierrez et al. (2015) reported a reduction of apparent ileal digestibility of dietary Lys when increasing amounts of reduced-oil DDGS were added to swine diets, which was not improved by the addition of dietary soybean oil. Results from this study also showed that feeding reduced-oil DDGS improved the digestibility of acid hydrolyzed EE, but decreased the digestibility of NDF in diets, but these effects were modulated by the addition of soybean oil.

Two studies (Graham et al., 2014a,b) have been published related to the impact of feeding reduced-oil DDGS sources on growth performance, carcass characteristics, and pork fat quality of growing-finishing pigs. In the first study (Graham et al., 2014a), increasing dietary inclusion (0 to 45%) of medium-oil (8.14% EE; DM basis) DDGS tended to reduce ADFI and linearly decreased ADG, G:F, final BW, HCW, and carcass yield of growing-finishing pigs. These results were contrary to a review of 20 studies by Stein and Shurson (2009) who concluded that growth performance responses could be maintained when up to 30% conventional high-oil (> 10%) DDGS were fed to pigs.

Reduction in growth and carcass responses observed in this study (Graham et al., 2014a) were mainly explained by the increased dietary fiber content with high dietary inclusion levels of DDGS, which may have limited feed intake, and that diets containing medium-oil DDGS likely had slightly decreased energy content than the control diets. However, diets fed in this study were formulated using static loading values derived from AA digestibility coefficients for the medium-oil DDGS. As a result, the risk of inaccurate diet formulation was increased because AA digestibility widely varied among DDGS sources. In the second study (Graham et al., 2014b) where DDGS with variable oil concentrations were fed, pigs showed inconsistent responses in growth performance and carcass composition to the change in oil content, which will be further discussed later in this chapter. This observation is consistent with results reported by Kerr et al. (2013) where oil content is a poor predictor of ME content in DDGS. More importantly, Graham et al. (2014b) suggested that IV of fat depots increased as DDGS level increased, and increased to a greater extent when diets containing DDGS with higher oil content were fed, which indicated that the reduced oil concentration diminished the negative impact of feeding DDGS on the pork fat quality.

Energy content of DDGS

Importance and economic significance of energy in swine diets

In swine production, feed represents about 60 to 70% of the total cost of production in farrow-to-finish operations, and the energy component represents the greatest proportion of the cost in swine feed (Noblet and Henry, 1993). Therefore, optimizing energetic efficiency of feed has been a primary goal for nutritionists to minimize production cost.

Dietary energy is a characteristic of feed that is produced through partial or complete oxidation processes of organic molecules during cellular respiration (Velayudhan et al., 2015). In the U.S., the typical unit of energy measurement in feed is calories, which is the amount of heat required to raise 1 gram of water 1°C (Pond et al., 1995). Unlike carbohydrates, amino acids, vitamins, minerals, and water, energy is not a nutrient, but is required for all biological processes (Kil et al., 2013). A portion of gross energy supplied in the diet will be lost in feces, and urine. Metabolizable energy is calculated by subtracting energy losses in feces and urine excreted from the GE consumed. Metabolizable energy intake in growing pigs can be partitioned into 2 functions: maintenance and growth. The pig's first priority is to meet its maintenance energy requirement which involves energy for basal metabolism, involuntary activities, and maintaining body temperature and homeostasis. Once this requirement is met, the remaining energy is used for productive purposes such as growth, lactation, or pregnancy (Velayudhan et al., 2015).

Cereal grains are the main feed ingredients that supply ME in U.S. swine diets, and include corn, sorghum grain, barley, wheat, oats, and their by-products such as corn DDGS (Holden et al., 2010). Supplemental fats and oils, such as choice white grease, tallow, corn oil, and soybean oil, are also added to swine diets as concentrated energy sources depending on the economic value of improvement in feed efficiency and cost of the supplemental fat.

Chemical composition of feed has a major impact on its energy content, because pigs utilize protein, starch, fiber, and lipids with different efficiencies (Patience, 2009). In general, the fibrous component of feedstuffs is less digestible than other nutrients. In

addition, the energy derived from fiber and protein components have a lower efficiency of utilization than starch and lipids for pigs because they require a series of intermediate metabolic biochemical steps to be converted to useable forms of energy in the body (heat increment; Noblet and van Milgen, 2004). Conversely, using fat and starch sources generate minimal amount of energy "wasted" in heat increment because they are highly digestible and can be readily used by pig. Therefore, accurate determination of energy values for feed ingredients and utilization efficiencies are essential to optimize caloric efficiency of swine diets.

Energy utilization systems for swine

Several energy systems have been developed to represent the energy value of feed, assess the metabolic utilization of feed energy, and also determine the animal's energy requirements (Velayudhan et al., 2015). The optimal energy system should be precise and generally applicable (Van Es, 1980), and ultimately, the "quality" of an energy system is based on its ability to predict animal performance as well as the energy value of both raw materials and compound feeds (Noblet and Henry, 1993).

Pigs do not completely utilize all of the GE in feed, but the proportion of dietary energy used for body functions cannot be measured by direct quantification. Therefore, available energy contained in the diet is often determined indirectly by subtracting energy loss in feces, urine, gases, and heat production from the GE content in diet (Kil et al., 2013). Based on these approaches, energy content of feedstuffs can be classified into GE, DE, ME, and NE (NRC, 2012; Figure 1.4). In the U.S., the ME system is used predominantly for corn and soybean meal based swine diets, but in Europe and western

Canada where more diverse feed ingredients are fed to pigs, the NE system has been more commonly used (Patience, 2009).

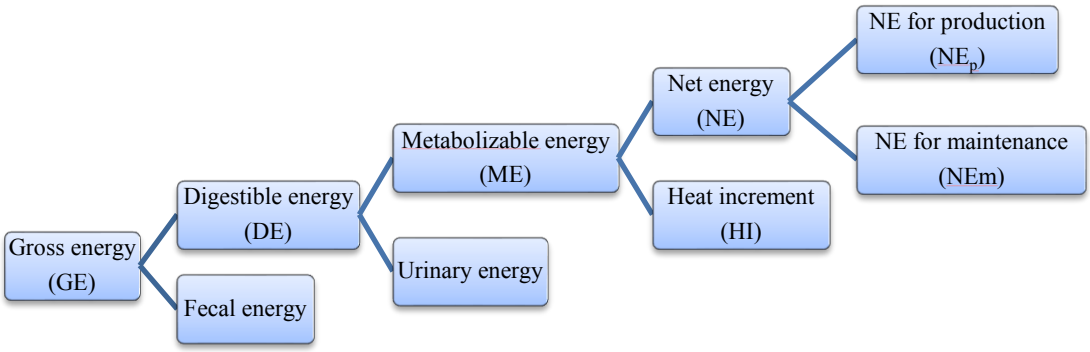

Figure 1.4. Partitioning of dietary energy in swine. Modified from Ewan (2001).

Gross energy refers to the amount of energy (or heat of combustion) produced when organic materials are completely oxidized. Gross energy can be measured using bomb calorimetry, and the concentration of GE in a feedstuff is dependent on its chemical composition. Gross energy values of 3.7, 4.2, 5.6, and 9.4 kcal/kg have been determined for glucose (and simple sugars), starch (and cellulose), protein, and lipids, respectively (Atwater and Bryant, 1900). As a consequence of the increased concentrations of lipids, protein, and fiber resulting from starch conversion to ethanol during fermentation, DDGS contains a greater concentration of GE (5,434 kcal/kg DM; Stein and Shurson, 2009) than corn (4,454 kcal/kg DM; NRC, 2012). However, GE is rarely used in diet formulation except for computational purposes, because it is totally independent of an animal's energy requirement, and provides little information on the bioavailability of energy for pigs (Velayudhan et al., 2015).

Digestible energy is calculated by subtracting the energy loss in feces from dietary GE, which is an apparent measurement of dietary digestible energy because the GE in feces is not partitioned between endogenous loss and feed origin (NRC, 2012). The average DE value of DDGS (4,140 kcal/kg DM) reported by Stein and Shurson (2009) is slightly greater than that of corn (3,908 kcal/kg DM; NRC, 2012). Whereas, energy digestibility (as a percentage of GE) is 14.7% lower in DDGS compared with corn (Mendoza, 2013). Gross energy of DDGS is less digestible due to its high fiber content, which is resistant to enzymatic digestion in the small intestine, but can be partially utilized with less efficiency, through bacterial fermentation and production of short chain fatty acids in the hindgut (Shi and Noblet, 1993; Noblet and van Milgen, 2004). In addition, dietary fiber also increases endogenous nutrient losses and passage rate of digesta, and consequently, reduces the digestibility of other nutrients (Noblet and Le Goff, 2001). For instance, Kim et al. (2013) showed that the digestibility of acid-hydrolyzed EE content of DDGS on an ileal and total tract basis was 50.1 and 51.9%, respectively, which was substantially less compared with extracted corn oil (95.4 and 94.3%, respectively).

Metabolizable energy is calculated by subtracting the excreted energy in urine and gases from DE. In pigs, gas losses are often overlooked in calculation of ME because they represent only a small fraction of total energy losses (0.5% to 3%; NRC 2012) and are difficult to measure. However, greater gas losses have been observed when hindgut fermentation is increased by increasing dietary fiber and BW of pigs (Kil et al., 2013; Noblet and van Milgen, 2004). The major factor that determines ME content of an ingredient or complete diet in pigs is the urinary energy loss, which is highly dependent

on the excreted N in urine (NRC, 2012). Urinary N excretion, in turn, is primarily affected by the digestibility and concentration of dietary CP. Consequently, the quality and quantity of protein in the diet relative to pig's requirement affects the ME to DE ratio (Velayudhan et al., 2015). However, even though the ME value only accounts for energy losses in urine, the energy cost for urinary excretion (e.g. energy lost in synthesizing urea) is not considered in ME system (Kil et al., 2013; Birkett and de Lange, 2001a). As previously discussed, DDGS contains a relatively high concentration of CP with poor protein quality, and when combined with the relatively high fiber content, it results in greater energy losses from urine and gas production that are not included in the ME determination. As a result, the amount of available energy in DDGS is likely overestimated in the ME system.

Net energy is defined as the difference between ME content and heat increment (**HI**). Net energy can be further partitioned into: 1) NE for maintenance (**NE_m**) used to support basic physiological functions of animals, such as the energy cost for keeping the animal alive and maintaining body temperature; and 2) NE for production (**NEp**) which is the proportion of the feed energy supplied in excess of the maintenance requirement and is used for protein and fat accretion, milk production, and conceptus growth (Stewart, 2007). Heat increment is the energy loss generated during digestive and metabolic processes of nutrient digestion and assimilation, tissue accretion, fermentation, and waste formation (NRC 2012), which is not used for productive purposes, but can be utilized for maintenance of body temperature in a cold environment (Velayudhan et al., 2015). First, pigs have variable HI depending on composition of diets because the efficiency of utilizing dietary energy varies with different chemical components. Noblet and van

Milgen (2004) suggested that the energetic efficiencies of ME (NE to ME ratio) are greater for dietary fat (approximately 90%) and starch (approximately 82%), but are relatively lower (approximately 60%) for dietary CP and fiber. Secondly, NE to ME ratio can also vary according to the particular biochemical pathways for the purpose of production (maintenance, growth, milk secretion, and protein and fat deposition; Noblet et al., 1994a), and consequently, it changes with stage of growth of pigs (Kil et al., 2013). For example, the energetic efficiency of ME for lipid retention is greater than that for protein retention and body maintenance, and finishing pigs are known to deposit more lipids than growing pigs. Therefore, the NE content of a given diet tends to be greater for finishing pigs compared with growing pigs (Kil et al., 2013). In conclusion, by accounting for heat increment, NE is the only system that accurately estimates the amount of energy in feed that is actually available for the pig (Noblet and van Milgen, 2004). As a result, the NE system is a much better predictor of growth performance and body composition of pigs compared with the DE and ME systems, especially for the use in diets containing high-fiber ingredients like DDGS.

NRC (2012) model for estimating energy intake responses in growing-finishing pigs

Dietary nutrient requirements vary by age and production phase of pigs because the requirements are influenced by the animal's physiological stage, genetic potential for growth, and environmental conditions (NRC, 1998). Mathematical models have been developed by NRC (2012) to dynamically estimate nutrient requirements for nursery and growing-finishing pigs, as well as gestating and lactating sows. Only the growing-finishing pig model will be discussed herein. Since nutrient requirements are established according to the animal's growth performance (especially ADFI), the NRC (2012) model

also calculates estimates of pig growth responses (ADFI, ADG, and G:F) based on dietary energy content and growth potential of pigs.

The NRC (2012) model uses 3 major factors – body composition, energy and feed intake, and partitioning of energy intake for various purposes – using a mechanistic approach to predict growth performance and nutrient requirements for growing-finishing pigs.

1) For body composition, growth of the pig is represented by changes in whole-body protein mass (**BP**) and whole-body lipid mass (**BL**), which are based on the daily rates of protein deposition (**Pd**) and lipid deposition (**Ld**), respectively. Chemical composition of BW gain varies with stage of growth and pig genotype. Thus, estimation of body composition (BL to BP ratio) is an important factor in the estimation of pig growth, which is calculated dynamically using iterative procedures in the model (NRC, 2012).

2) Feed intake of pigs can be predicted based on the combination of required energy intake, user-defined diet energy density, and a defined rate of feed wastage. Therefore, one of the key steps in predicting growth performance is to estimate the required energy intake of pigs at various BW. The model provides three options: A) prediction of energy intake from BW and additional factors such as gender, physical feed intake capacity, environmental temperature, and pig density; B) User-defined energy intake curves based on inputs of observed feed intake over a defined BW range, which is then used in combination with the reference energy intake curve; or C) Energy intake curves can also be defined using mathematical equations with user-defined parameters (NRC, 2012). Option B allows users to modify the energy intake curve according to

previous observations and therefore, will be used in describing the NE estimation approaches for experiments described in this thesis.

3) Partitioning of energy intake is based on the physiological priority that the pig must first satisfy its maintenance requirements. Energy intake that is not used for maintenance functions is used for Pd and Ld. Maintenance energy requirements are predicted from BW and adjusted for environmental temperatures in the model. Heat production/loss and energy intake of an animal can be affected when environmental temperature deviates from the pig's thermoneutral zone (NRC, 2012). Pigs tend to increase ADFI when temperature is below the lower critical temperature, and to decrease ADFI when temperature is above the upper critical temperature. Next, to calculate the Pd and Ld rates, Pd curves need to be defined by users using one of the 3 options offered in the model: A) Users enter observed mean Pd value (between 25 and 125 kg BW) and gender of pigs, which are then combined with a standard gender-specific Pd curve to calculate Pd rate at any specific BW; B) Daily Pd is calculated from BW using mathematical equations and user-defined parameters; or C) Pd rate can also be determined according to the relationship between Pd and energy intake; values for the maximum Pd rate ($\mathbf{Pd_{max}}$) and the BW at which Pd_{max} starts to decline are required inputs (NRC, 2012). Among the parameters required by these options, mean Pd rate can be obtained using equations from NPPC (2000) and observed carcass composition from previous experiments. Option A was used in our experiments to estimate the nutrient requirements for diet formulation and to predict pig growth performance.

The NRC (2012) growth model allows users to define the energy content of the diet on either a ME basis or NE basis. However, effective ME is used as the calculation

unit of energy in the model, because it accounts for the different efficiencies of energy utilization by pigs for different purposes (e.g. protein and lipid accretion). In the NRC (2012) model, effective ME is calculated from NE value of diets using fixed conversion efficiencies: 0.72 for starting pigs (5 to 25 kg BW), 0.75 for growing-finishing pigs (25 to 135 kg BW), or 0.763 for sows (NRC, 2012). As NRC (2012) suggests, NE is the preferred method to use when predicting the pig's responses to energy intake. As a result, there is a potential application of the model to reverse calculate NE content of diets by matching the predicted and observed pig growth performance, which will be described in chapter 3.

Determination of energy content of DDGS for swine

Chemical composition of DDGS varies widely among sources and contributes to the wide variability in energy concentrations. Consequently, precise and dynamic determination of energy values for DDGS sources is important for correct diet formulation and to achieve optimal economic value and caloric efficiency when using DDGS in swine diets. Methods have been developed to determine or predict DE, ME, and NE values of feedstuffs, but the methodology used differs among research groups, which may also partly explain the variation in determined energy values among DDGS sources.

Digestible and metabolizable energy

Several methods have been developed to measure the DE and ME content of diets fed to pigs, including traditional metabolism studies (total collection and index methods), as well as the use of growth assays (Mendoza, 2013). When determining energy

digestibility of feeds in pigs, intake of total feed energy (GE) and the amount of energy excreted in the feces resulting from feed consumed need to be quantified.

When the total collection is used, pigs are confined to individual metabolism crates where feces originating from the test feed during the entire collection period are collected. Indigestible markers, which are colored compounds such as ferric oxide, indigo carmine, and chromic oxide, can be fed as a part of the first meal to identify the beginning of the collection period, and fed a second time as a part of the last meal to mark the end of the collection period (Adeola, 2001). When pigs are transferred into metabolism crates, an adequate adaptation period is required before the collection period to let pigs to adapt to the crates and the test diets, which is essential for the accuracy of a digestion study. An adaptation period of 3 to 7 days followed by a collection period of 4 to 6 days is commonly used (Adeola, 2001). However, an extended adaptation period may be necessary for testing feedstuffs that contain high fiber components, because the adaptation of microbial fermentation of fiber takes a longer time than that for other nutrients (Longland et al., 1993). In studies that determined energy and nutrient digestibility of DDGS sources, an adaptation period of 5 days (Stein et al., 2009; Adeola et al., 2014), 7 days (Pedersen et al., 2007; Dahlen et al., 2011), or 9 days (Anderson et al., 2012; Liu et al., 2012; Kerr et al., 2013) was commonly used. If indigestible markers are not used, feces collection starts at the same time when the experimental feeding period begins and ceases as the experimental period stops. In this system, longer adaptation and collection periods (usually 5 to 7 days) are needed, and a constant feeding level should be maintained from late adaptation period until the end of collection period to minimize the error of incorrect collection of feces originated from meals fed prior to

the initiation of collection period (Young et al., 1991). In a total collection study, level of feeding used can affect the results of energy measurement, because it may change the relative proportions of endogenous microbial and dietary contributions to the feces and also influence the passage rate of digesta through the digestive tract (Young et al., 1991). Typically, a daily feeding level of 3.5 times maintenance, or about 4% of BW, is provided for pigs less than 50 kg BW, and feeding level is reduced to 2.5 to 3.5 times maintenance, or 2.7 to 4% of BW, when pig BW increases above 50 kg (Adeola, 2001). Samples of feed and feces collected are weighed and analyzed for the GE content to calculate the total GE intake and GE output by pigs. Energy digestibility is then calculated using equation:

$$\text{Energy digestibility}, \% = 100 \times \left(\frac{\text{GE intake} - \text{GE output}}{\text{GE intake}}\right)$$

To estimate ME content, the energy loss in urine is quantified and subtracted from DE. Since urine is accumulated in bladder and voided periodically, it is difficult to identify the urine originated from specific meals. Therefore, collection of urine often starts and ends when the markers are fed for the first and second times, respectively (Adeola, 2001). Urine samples are then dried (oven-drying or freeze-drying) and analyzed for GE content.

Use of the index method involves mixing an inert marker, such as titanium dioxide (TiO_2), chromic oxide (Cr_2O_3), and acid insoluble ash, with the diet to label the meal as it passes through the digestive tract, rather than using total fecal collection. An ideal marker for determination of digestibility values should be totally indigestible, non-absorbable, and pharmacologically inactive within the digestive tract, and it should pass through the tract at a uniform rate and be readily determined chemically (Jagger et al.,

1992). Therefore, it can be assumed that the amount of index compound in the feed and the amount voided in the feces are similar over equal periods of time (Adeola, 2001). Recovery rate is an important indication of the efficacy of a marker. Studies have shown that TiO_2 is a more suitable marker than Cr_2O_3 based on a greater recovery rate (Jagger et al., 1992; Yin et al., 2000), and that Cr_2O_3 is superior to acid insoluble ash for estimating digestibility in pigs (Bakker and Jongbloed, 1994; Van Leeuwen et al., 1996).

Using the index method, fecal samples are collected and analyzed using similar processes as in the total collection method, and energy digestibility of a diet is calculated as follows:

$$\text{Energy digestibility, \%} = 100 - 100 \times \left(\frac{\text{\% index compound in feed} \times \text{GE of feces}}{\text{\% index compound in feces} \times \text{GE of feed}}\right)$$

Since the use of index compounds avoids total collection of feces, this system does not require housing pigs in metabolism crates. However, if pigs are not confined and urine is not collected, the use of index method only provides estimates for DE and not the ME content of the test diets.

Total collection, as a preferred method, provides a biological model that best represents the actual digestion and nutrient utilization of pigs. However, disadvantages of using total collection include long experimental duration, extensive labor and cost, and potential animal welfare concerns (Anderson, 2009). Although the index method allows a faster and less expensive assessment of feed energy, questions arise regarding its potential error in determining energy digestibility. Adeola (2011) suggested that using chromic oxide or titanium oxide as index compounds resulted in similar energy digestibility values for a corn diet or complete feed compared with using the total collection method. However, for feedstuffs (e.g. triticale) that have sticky characteristics,

the index marker may not mix uniformly with the digesta as it passes through the digestive tract, causing an inaccurate determination of energy digestibility.

Energy digestibility of a feed ingredient (a component of a test diet) can be determined using the direct or indirect approach. If an ingredient can be fed alone as the exclusive energy supplier in the diet, energy digestibility is determined directly using either the total collection or index methods described previously. In contrast, for ingredients (e.g. protein and lipid supplements) that cannot be fed independently due to palatability or formulation restrictions, use of a basal diet is needed and energy digestibility is calculated indirectly (Adeola, 2001). In this situation, a group of pigs is fed a basal diet to determine the energy digestibility of the basal diet. Simultaneously, another group(s) of pigs is used to determine the energy digestibility of diets with a known quantity of the test ingredient added to basal diet, or with a proportion of basal diet substituted by the test ingredient. Energy digestibility of the test ingredient is then determined by the difference between the digestibilities of basal diet and diets containing a specific proportion of basal and test ingredients, or measured by regression of the digestibilities of diets against the proportions of the test ingredient replaced and extrapolated to 100% replacement (Adeola, 2001).

Other than the traditional metabolism studies described above, growth assays have also been used to estimate ME content of DDGS sources. Groups of pigs are fed test ingredients with increasing amounts of dietary ME by adding fiber or lipid to the diets. Linear responses in pig growth performance (usually G:F) are then used in regression analysis to estimate ME value of the test ingredient (Hastad et al., 2004). A summary of studies that have determined ME of DDGS sources is presented in Table 1.2.

Hastad et al. (2004) determined ME (as-fed basis) content of DDGS using a metabolism study and growth assay. In the metabolism study, the 2 sources of DDGS evaluated had a mean ME of 3,642 kcal/kg, which was slightly greater than the ME content of corn suggested by NRC (2012). In contrast, the mean ME (3,311 kcal/kg) content determined by the growth assay was about 9% less than the value obtained using the metabolism study, which confirmed that using different methodologies contributes to the variation in estimated ME values for DDGS.

In an energy balance experiment conducted by Stein et al. (2005), 4 sources of DDGS had an average ATTD of GE (DE/GE) of 75% and ME (DM basis) concentration of 3,378 kcal/kg, and no significant differences among sources were observed. This ME value was about 12.1% lower than the ME value of corn in NRC (2012).

With a greater sample size, Pedersen et al. (2007) determined ME content of 10 sources of traditional DDGS sources with medium- or high-oil concentrations (8.6 – 12.4% EE) in a total collection metabolism study. The 10 sources of DDGS had variable ATTD of GE between 73.9 and 82.8%, which were substantially lower than the energy digestibility of the corn basal diet (90.4%) used in the experiment. Concentrations of ME (DM basis) ranged from 3,674 to 4,336 kcal/kg and significant differences were observed among sources. The mean ME content (3,897 kcal/kg) of these DDGS sources was similar to the reference ME content of corn (NRC, 2012).

Subsequently, Stein et al. (2009) conducted a metabolism study involving 4 sources of DDGS containing traditionally high, and similar levels of oil content (> 10% EE). Sources of DDGS used in this study were selected from ethanol plants that used similar production technologies and were derived from similar corn sources that were

grown within a narrow geographical area. However, researchers observed significantly different ATTD of EE and NDF, and a tendency for variation in ATTD of GE, among DDGS sources. These variations in nutrient digestibility led to a significant difference in ME concentrations of DDGS sources, but the mean ME value (3,750 kcal/kg DM) was comparable to that of corn suggested by NRC (2012).

Dahlen et al. (2011) determined the ME content of a conventional corn DDGS and a low-solubles DDGS source, which contained similar EE content of 8.0 and 8.9%. Results from this study showed that the ME content of the 2 DDGS were not different (2,959 vs. 2,964 kcal/kg DM), and were approximately 23% less than the ME value of corn (NRC, 2012).

After ethanol plants began using oil extraction technology to produce reduced-oil DDGS in 2007, several studies were conducted to investigate the impact of reduced-oil content on the energy value of DDGS sources. Jacela et al. (2011) conducted a digestibility trial involving a low-oil (solvent-extracted) corn DDGS source with 4.6% EE content. Concentration of DE in this DDGS source was found to be greatly reduced relative to the DE content of corn (3,100 vs. 3,908 kcal/kg, respectively) reported by NRC (2012). Metabolizable energy was not measured in this study, but was calculated to be 2,858 kcal/kg using a prediction equation (ME = 1.00 × DE – 0.68 × CP; Noblet and Perez, 1993). Using a similar approach, Graham et al. (2014a) determined DE (3,582 kcal/kg) and calculated ME (3,365 kcal/kg) values for a medium-oil (8.1% EE) DDGS source, which were 8.0% and 12.5% less, respectively, than the DE and ME of corn (NRC, 2012). In a subsequent digestibility study, Graham et al. (2014b) determined the nutrient and energy digestibility of 4 sources of DDGS with variable oil content. Large

variations in ATTD of GE (76.1 to 81.3%), EE (61.8 to 75.6%), and NDF (51.4 to 72.0%) were observed among DDGS sources. Metabolizable energy values of the 4 sources of DDGS were calculated using the Noblet and Perez (1993) equation. Although the 5.9% oil DDGS contained the lowest ME concentration (3,481 kcal/kg DM) among the 4 sources, ME value of the 13.0% oil DDGS (3,798 kcal/kg DM) was similar to that of the 10.4% oil DDGS (3,793 kcal/kg DM), and was even lower than ME of the 10.1% oil DDGS (3,905 kcal/kg DM). These results again showed that only using oil concentration as a predictor of ME content in DDGS sources results in inaccurate estimations. However, it should be noted that the calculation of ME content of DDGS using the Noblet and Perez (1993) prediction equation is questionable because it was developed based on complete feeds with balanced nutrient composition, and caution is needed when applying it to single feed ingredients, such as DDGS, which have relatively high concentrations in specific chemical contents (e.g. CP and fiber).

Anderson et al. (2012) measured the ME values of 7 samples of DDGS including 6 conventional high-oil (> 10% EE) DDGS sources, and 1 DDGS source that contained only 3.2% EE. Metabolizable energy values of high-oil DDGS sources varied from 3,414 to 4,141 kcal/kg with an average of 3,790 kcal/kg. In contrast, the oil-extracted DDGS source had a ME concentration of 3,650 kcal/kg that was within the range of ME values of high-oil DDGS sources. This was the first study to show that less oil content in DDGS does not correspond to lower ME values.

More recently, ME concentrations of 15 DDGS sources with EE content varying from 4.9 to 13.2% were determined by Kerr et al. (2013). Variations in ATTD of GE (68.3 to 79.1%), EE (52.7 to 81.2%), and NDF (44.5 to 61.5%) content were observed

among DDGS sources. Concentrations of ME in DDGS sources varied from 3,266 to 3,696 kcal/kg with a mean ME value (3,435 kcal/kg) that was 10.7% less compared with corn ME content (NRC, 2012). However, the variation in ME values did not correspond to the EE concentrations of DDGS sources (ME, kcal/kg = 3,103 + 30.28 × EE, %; R^2 = 0.11, P = 0.31), and therefore, this study confirmed that EE was a poor predictor of ME for DDGS.

Table 1.2. Summary of published estimates for ME (kcal/kg DM) content of corn distillers dried grains with solubles (DDGS) relative to ME content of corn (NRC, 2012)

Item	n	ME of DDGS				DDGS relative to corn[1] (%)
		Average	Least value	Greatest value	SD	
Hastad et al., 2004[2]	2	4,047	3,986	4,108	-	105.3
Hastad et al., 2004[3]	2	3,679	3,476	3,882	-	95.7
Stein et al., 2005	4	3,378	-	-	-	87.9
Pedersen et al., 2007	10	3,897	3,674	4,336	221	101.4
Stein et al., 2009	4	3,750	3,575	3,976	168	97.6
Dahlen et al., 2011	2	2,962	2,959	2,964	-	77.0
Jacela et al., 2011[4, 5]	1	2,858	-	-	-	74.3
Liu et al., 2012	3	3,730	3,583	3,862	140	97.0
Anderson et al., 2012	6	3,790	3,414	4,141	252	98.6
Anderson et al., 2012[5]	1	3,650	-	-	-	94.9
Kerr et al., 2012[5]	15	3,435	3,266	3,696	140	89.3
NRC, 2012, > 10% oil	-	3,845	-	-	-	100.0
NRC, 2012, > 6 and < 9% oil	-	3,801	-	-	-	98.9
NRC, 2012, < 4% oil	-	3,476	-	-	-	90.4
Graham et al., 2014a[4, 5]	1	3,365	-	-	-	87.5
Graham et al., 2014b[5]	4	3,744	3,481	3,905	183	97.4
Adeola et al., 2014	1	3,559	-	-	-	92.6

[1] Average ME of DDGS sources as percentage of ME value of corn from NRC (2012).

[2] ME of DDGS determined using metabolism study. Moisture content was not reported, and values were presented on DM basis assuming 89.3% DM (NRC, 2012).

[3] ME of DDGS determined using growth assay. Moisture content was not reported, and values were presented on DM basis assuming 89.3% DM (NRC, 2012).

[4] ME was calculated using equation from Noblet and Perez (1993) based on determined DE and analyzed chemical composition.

[5] Studies involved reduced-oil (< 10%) DDGS sources.

Net energy

To determine the NE content of a feedstuff, one needs to measure either the retention of energy (**RE**) or heat production (**HP**) of pigs fed the test diet, as well as the pig's energy utilization to meet maintenance requirements (**NE_m**) ($NE = RE + NE_m$; Velayudhan et al., 2015). In North America, the most commonly used methods for NE determination in swine have been comparative slaughter and indirect calorimetry.

The comparative slaughter method involves determining the body composition of two groups of similar (gender, age, and genotype) pigs at the beginning and end of the feeding period (Blaxter, 1989). When comparative slaughter is used, RE is defined as the difference between the total body energy content of initial and final whole body composition of slaughter groups, and the GE content of the carcasses is measured by bomb calorimetry. The NE_m is obtained using equations based on the mean metabolic BW of the pigs. Although the comparative slaughter method is regarded as the "gold standard" for determining NE content of diets and feed ingredients, it is very labor-intensive, requires a relatively large number of animals, and it does not allow repeated measurements (Velayudhan et al., 2015).

Alternatively, Dual-energy X-ray Absorptiometry (**DXA**) method has been recently developed to determine the NE content of feedstuffs using a similar calculation process similar to the comparative slaughter method ($NE = RE + NE_m$), but with a more convenient and non-destructive approach to measure total lean, fat, and bone composition of live pigs (Suster et al., 2004; Kerr et al., 2015). Initial and final body composition of pigs are determined using DXA. Energy retention is calculated from whole body protein, fat, and bone accretion (difference between initial and final body composition) assuming

1 g of protein contains 5.54 kcal and 1 g of lipid contains 9.34 kcal (Birkett and DeLange, 2001b). The DXA method avoids an inherent error in comparative slaughter method, which is the assumption that pigs from initial and final slaughter groups have identical body composition at the initiation of the feeding period. However, using this method requires very expensive equipment for DXA measurement.

In contrast to the direct determination of RE using comparative slaughter and DXA methods, RE can also be measured as the difference between ME intake and the total amount of HP that a pig generated for both maintenance (NE_m) and non-productive (HI) purposes. Heat production of living organisms is determined using indirect calorimetry by measuring their consumption of O_2, production of CO_2, and N excretion (Velayudhan et al., 2015). In this method, a metabolism study is usually conducted first to determine the ME content of the test feedstuffs. Subsequently, pigs are transferred into respiration chambers for the measurement of gaseous exchange and urinary N excretion during a feeding and fasting period (Ayoade et al., 2012). Fasting heat production (**FHP**) is then used as an estimate of the NE_m. Finally, NE concentration of the test diet is calculated using the following equations (Ayoade et al., 2012): RE = ME – HP and NE = (RE + FHP)/DM intake. Similar to the ME determination method described previously, NE content of a single ingredient (DDGS) is typically determined using an indirect (difference) procedure by subtracting the NE contribution by a basal diet from the NE of the diet containing test ingredient. The indirect calorimetry method offers a relatively faster approach for determining NE content of a feed ingredient, requiring fewer animals and allows repeated measurements compared with comparative slaughter method, but it also requires sophisticated and expensive equipment (Velayudhan et al., 2015).

A limited number of studies have been conducted to determine the NE (DM basis) content of DDGS sources (Table 1.3). Using the comparative slaughter method, Gutierrez et al. (2014) determined NE concentrations of a conventional DDGS source (13.0% EE) and an uncooked (enzyme-treated prior to fermentation) DDGS source (2.6% EE). The conventional DDGS source had a lower NE concentration when fed to pigs during the growing phase compared with the finishing phase (2,173 vs. 2,697 kcal/kg, respectively). However, the NE content of the uncooked DDGS source was not different between the growing and finishing periods (2,120 and 2,058 kcal/kg). The reason for markedly less NE value of uncooked DDGS compared with conventional DDGS in finishing phase, but not in growing phase, is unclear. Possibly, the higher oil concentration of conventional DDGS resulted in greater fat accretion by directly depositing dietary lipid compared with that of the uncooked DDGS source, and this effect was more prominent in the finishing phase because finishing pigs deposit much more carcass lipid than growing pigs (Gutierrez et al., 2014). Furthermore, these NE estimates for DDGS sources were lower than the NE value for corn (NRC, 2012), and were also reduced compared with NRC (2012) recommended NE values (2,669 kcal/kg for DDGS with > 10% oil and 2,251 kcal/kg for DDGS with < 4% oil) for DDGS sources according to their oil concentration. However, it is important to realize that the NE values suggested by NRC (2012) are questionable because these values are calculated using prediction equations developed based on complete feeds. More recently, Kerr et al. (2015) determined NE values of 6 corn DDGS sources using the DXA technique. Although oil concentrations of these DDGS varied from 7.0 to 13.3%, NE content were not different among sources (2,012 to 2,253 kcal/kg) with a mean value of 2,135 kcal/kg, which were 29.4 and 12.3% less than

the NE content of corn (NRC, 2012), and conventional DDGS (average between grower and finisher periods) determined by Gutierrez et al. (2014), respectively. Results from this study confirmed once again that oil content was not a good indicator of energy content among DDGS sources.

In other experiments, Graham et al. (2014b) estimated the NE concentrations of 4 DDGS sources by calculating and comparing the NE efficiencies of pigs fed DDGS diets with pigs fed a corn-soybean meal control diet and using NRC (2012) published values for NE content of corn and soybean meal. Estimated NE values ranged from 2,122 to 2,893 kcal/kg and appeared to be positively correlated to the EE concentration of DDGS (NE, kcal/kg = 1,501.01 + 115.011 × EE, %; adjusted $R^2 = 0.86$).

Table 1.3. Summary of published estimates for NE (kcal/kg DM) content of corn distillers dried grains with solubles (DDGS)

Item	n	NE of DDGS				DDGS relative to corn[1] (%)
		Average	Least value	Greatest value	SD	
Gutierrez et al., 2014[2]	1	2,435	-	-	-	80.5
Gutierrez et al., 2014[3]	1	2,089	-	-	-	69.1
Graham et al., 2014b	4	2,551	2,122	2,893	318.8	84.3
Kerr et al., 2015	6	2,135	2,012	2,253	89.2	70.6
NRC, 2012, > 10% oil	-	2,384	-	-	-	78.8
NRC, 2012, > 6 and < 9% oil	-	2,343	-	-	-	77.4
NRC, 2012, < 4% oil	-	2,009	-	-	-	66.4

[1] Average NE of DDGS sources as percentage of NE value of corn from NRC (2012).
[2] Conventional DDGS source.
[3] Uncooked (enzyme-treated prior to fermentation) DDGS source.

Nutritional factors that contribute to ME and NE variability among sources

Several factors appear to affect variability in ME and NE content among DDGS sources. First, as discussed in previous sections, differences in raw materials and processing technologies used in DDGS manufacturing have resulted in inconsistent chemical composition of DDGS among sources and even among batches, which

contributes to a variation in ME and NE content. Pedersen et al. (2007) reported highly variable ME content among 10 DDGS sources, with a difference of 662 kcal/kg between the high and low ME sources (Table 1.2). Stein et al. (2009) reported that the range in ME content among 4 DDGS sources was 401 kcal/kg. Similarly, a wide range in ME content, with a difference of 727 kcal/kg, was reported among 7 sources of DDGS evaluated by Anderson et al. (2012). Graham et al. (2014b) also observed that 4 sources of DDGS with variable oil content exhibited a marked difference of 771 kcal/kg in NE content between the highest and lowest sources.

Nutrient content (lipid, fiber, and protein) and digestibility varies among DDGS sources. Kim et al. (2013) reported that only about 50% of the oil in DDGS is digestible for swine, and Kerr et al. (2013) reported that ATTD of EE ranges from 53 to 81% among sources. Furthermore, Urriola et al. (2010) reported that ATTD of TDF in DDGS for swine ranged from 29 to 57%. Differences in EE and fiber digestibility among DDGS sources appear to be due to differences in the porosity of the fiber-starch-protein matrix in various DDGS sources, which affects fermentability of fiber and effectiveness of carbohydrase enzymes (Jha et al., 2015). In addition, SID of CP in DDGS varies from 67 to 80% (Urriola et al., 2009), and reduction in oil content may further decrease SID for most AA in DDGS (Curry et al., 2014).

Particle size also differs among DDGS sources. Liu et al. (2012) determined the ME values of 3 samples of DDGS that originated from the same source, but differed in particle size. Results from this study suggested that ME values increased from 3,583 to 3,862 kcal/kg DM when particle size of DDGS decreased from 818 to 308 μm. Finally, different methodologies used in energy determination studies may contribute to

variability in ME and NE estimates. Hastad et al. (2004) showed that using traditional metabolism study and growth assay methods resulted in a 331 kcal/kg difference in ME content of the same DDGS sources. In contrast, Ayoade et al. (2012) determined the NE content of a complete diet containing a wheat and corn blend DDGS using 3 different methods (comparative slaughter, indirect calorimetry, and prediction based on chemical composition), and reported that the dietary NE values obtained by these methods were not different. However, this experiment did not measure and compare the NE values for single feed ingredients.

Prediction of ME and NE content of DDGS sources from chemical composition

As an alternative to traditional metabolism trials, prediction equations based on analyzed chemical composition can be used as a dynamic, fast, and inexpensive method to estimate ME and NE content of a feedstuff. Two ME prediction equations (Eq. 1-5 and 1-6) were included in the current NRC (2012). These equations were adopted from a research study conducted by Noblet and Perez (1993) where ME content of 114 complete diets was measured, and ME predictions were developed based on determined DE content, or from chemical composition of test diets. However, the accuracy and precision of using these equations to estimate ME and NE content of single feed ingredients is questionable. Therefore, studies have been conducted to develop specific ME equations for DDGS sources.

Pedersen et al. (2007) developed 5 equations using 10 sources of traditional high-oil DDGS, and R^2 of these equations ranged from 0.94 to 0.99. Based on a wider variety of corn co-products, including 7 samples of DDGS, Anderson et al. (2012) published 8 ME equations with R^2 ranging from 0.43 to 0.99. More recently, Kerr et al. (2013)

evaluated a total of 15 DDGS samples, including DDGS sources that were subjected to oil-extraction, and 9 equations (R^2 from 0.31 to 0.99) were developed for predicting ME and ME to DE ratio. However, with the many different energy prediction equations available, it has been a challenge for users to identify the "best" equation to use based on variable R^2 values and other statistics (e.g. residual standard deviation; **RSD**) reported in these studies. To solve this problem, Urriola et al. (2014) conducted a cross-validation study where more than 19 published DE and ME equations (Pedersen et al., 2007; EvaPig®, 2008; Anderson et al., 2012; Kerr et al., 2013) were evaluated using complied database of 45 DDGS sources from 5 studies (Stein et al., 2006, 2009; Pedersen et al., 2007; Anderson et al., 2012; Kerr et al., 2013). By comparing the R^2, prediction error, and prediction bias of test equations, Urriola et al. (2014) concluded that using the combination of equations: DE = -2,161 + (1.39 × GE) – (20.7 × NDF) – (49.3 × EE) and ME = -261 + (1.05 × DE) – (7.89 × CP) + (2.47 × NDF) – (4.99 × EE) from Anderson et al. (2012) resulted in the most accurate and precise prediction of ME content for DDGS sources with variable oil content. However, these equations require further validation to determine their accuracy and precision in achieving expected growth performance and carcass composition of pigs.

For predicting the NE content of diets, Noblet et al. (1994b) proposed a system (the "French NE system") based on 61 measurements of diet DE, ME, and NE for growing pigs. Concentrations of NE in 61 diets were measured using indirect calorimetry, from which a total of 11 NE equations were developed (R^2 and RSD ranged from 0.89 to 0.97 and 40 to 82 kcal/kg, respectively). Out of these 11 equations, Eq. 5 and Eq. 8 were adopted in NRC (2012), and were used to calculate NE values for feed ingredients. As an

extension of the French NE system, researchers from Central Bureau Livestock Feeding (CVB) in Netherlands developed another equation (the "Dutch NE system") to estimate the NE values of feeds and feed ingredients based on digestible nutrient composition (e.g. CP, EE, starch, digestible sugars, and fermentable carbohydrates). The Dutch NE system is different from the French NE system, because is separates total digestible carbohydrates into an enzymatically-digestible fraction and a fermentable fraction, and also uses different procedures to determine the digestibility of nutrients (Kil et al., 2013). However, given the difficulties in obtaining the digestibility coefficients for nutrient fractions not commonly determined in commercial laboratories, limited data are available to evaluate the use of this equation for DDGS.

In contrast to the prediction of ME, development of NE equations specific for DDGS sources has been limited. In a recent study, Graham et al. (2014b) reported a simple NE equation based on 4 sources of DDGS and used EE content as the only predictor variable (NE, kcal/kg = 1,501.01 + 115.011 × EE, %; adjusted R^2 = 0.86). However, this approach ignores the findings reported by Kerr et al. (2013) that oil content is a poor predictor of DE and ME content of DDGS sources. In addition, further evaluation of the precision and accuracy of the Graham et al. (2014b) equation is needed because the NE values of the 4 DDGS sources were not determined using a traditional metabolism study approach, but rather were estimated by comparing the energetic efficiency of DDGS treatments with the control diet. In addition to prediction equations, commercial services (e.g. ILLUMINATE®; Nutriquest, Mason City, IA) have been developed to provide NE estimates for the majority of DDGS sources produced by U.S. ethanol plants. The prediction equations used in this commercial service are proprietary,

but are likely based on the chemical composition of DDGS sources and published equations.

In summary, to manage the energy variability among DDGS sources, dynamic determination of ME and NE content for DDGS is needed to optimize caloric efficiency and economic value of using reduced-oil DDGS sources in swine diets. However, due to the high cost and time required to conduct energy determination metabolism trials, nutritionists need more practical approaches to obtain accurate ME and NE estimates for DDGS sources with highly variable nutrient content. Empirical equations and commercial services provide fast and inexpensive predictions of ME and NE values for DDGS sources, but the precision and accuracy of these approaches need to be further evaluated. Therefore, chapter 2 of this thesis describes an experiment that was conducted to validate the use of the "best" ME prediction for 3 DDGS sources with variable oil content. Chapter 3 provides data to evaluate the published NE equations based on growth performance of pigs fed 4 sources of DDGS, and proposed a novel approach to estimate NE content of feed and feed ingredients using the NRC (2012) growth model.

Feeding DDGS to growing-finishing pigs

Effects on growth performance

In 2009, Stein and Shurson reviewed 25 experiments where growth performance of pigs fed diets containing corn DDGS at levels up to 30% of the diet, were compared with pigs fed diets containing no DDGS. Results of this review showed that ADFI was not affected in 65% of these experiments, but reduced in 26% of the reviewed experiments. Responses for ADG were unaffected in 72% of the experiments, but decreased in 24% of experiments, and G:F was unchanged in 64% of the studies, but was

reduced in 20% of experiments (Table 1.4). In a more recent review of 21 experiments by Hardman (2013), comparing growth performance responses when fed diets containing DDGS compared with pig performance when fed corn-soybean meal based diets, ADFI of pigs fed DDGS diets unaffected in 62% of the experiments, and decreased in 14% of experiments. For ADG, feeding DDGS diets resulted in unchanged or improvements in 62% of experiments, but was reduced in 24% of the studies, while G:F was not affected in 67% of these studies and decreased in 10% of the experiments. A number of factors have been proposed that may have contributed to reductions in ADG and G:F reported in some studies (Stein and Shurson, 2009; Hardman, 2013). These include: 1) use of inaccurate estimates of dietary energy and/or nutrient digestibility values in diet formulation; 2) overfeeding crude protein when high levels of DDGS were added in diets, which increases the energy cost of pigs to excrete excess AA; 3) some DDGS sources may be heat-damaged during the drying process and therefore, may be less digestible and palatable; and 4) sample size varies among studies resulting in differences in statistical power for detecting treatment differences.

When U.S. ethanol plants began extracting oil from thin stillage before manufacturing DDGS in 2007, concerns increased regarding the feeding value of DDGS in swine diets. A total of 16 experiments published after 2009 are summarized in Table 1.4 (studies reviewed by Stein and Shurson are not included). Average daily gain was reduced in 6 experiments, not affected in 10 experiments, and no studies reported improvements in ADG. For overall ADFI, improvements were found in 2 experiments, reductions in 6 experiments, and 8 studies showed ADFI to be unaffected. The G:F was increased in 2 experiments, decreased in 5 experiments, and not affected in 9

experiments. In contrast to the studies reviewed in Stein and Shurson (2009), there was greater variation in observed in growth performance responses to increasing levels of dietary DDGS in these studies, further emphasizing the need for using accurate energy and nutrient loading values in feed formulation.

Cromwell et al. (2011) conducted a cooperative study to evaluate the growth performance of pigs fed the same DDGS source at 9 different research stations. Experimental diets were manufactured at each station utilizing the same DDGS source and dietary levels (0, 15, 30, and 45%), but the other feed ingredients were obtained locally. Results from this study showed that increasing dietary DDGS inclusion linearly decreased ADG, but did not affect ADFI and G:F. However, there were significant differences among reported values from various locations. Therefore, other factors, such as climate, management strategies, and nutritional composition of other ingredients, can also lead to the variability in growth performance of pigs fed DDGS diets (Harris, 2014).

High dietary DDGS inclusion rates (> 30%) may have contributed to a larger number of studies reporting reduced ADFI, compared with the previous review by Stein and Shurson (2009). Among the 16 reviewed studies, 8 experiments involved feeding diets containing more than 30% DDGS. Maximum dietary inclusion rates of 40% were used by Hilbrands et al. (2013) and Graham et al. (2014a), 45% was used by Cromwell et al. (2011) and Graham et al. (2014b), and up to 60% was used by Bergstrom et al. (2009) and Hardman (2013). It has been suggested that increased bulkiness of dietary fiber in high DDGS diets limits the physical gut capacity of pigs, thus preventing them from achieving sufficient energy intake (Kennelly and Aherne, 1980).

Finally, partial oil extraction occurring in ethanol plants has increased variability in feeding value among DDGS sources. Graham et al. (2014b) measured the growth performance of finishing pigs fed 4 different sources of low-, medium-, and high-oil DDGS in two experiments. In experiment 1, ADG of pigs fed a 9.6% oil DDGS source was unaffected, but ADFI was reduced and G:F was improved compared with those fed 5.4% oil DDGS, regardless of the dietary inclusion level. However, in experiment 2, no differences in any growth performance criteria were observed among pigs fed 9.4% oil DDGS and pigs fed 12.1% oil DDGS diets. The inconsistent observations between the 2 experiments confirm that oil content is poor predictor of energy content in DDGS sources and may not adequately predict growth performance of pigs fed DDGS.

Table 1.4. Effects of corn distillers dried grains with solubles (DDGS) in diets fed to growing-finishing pigs on growth performance and carcass characteristics

		Response to increasing dietary DDGS, No. of experiments		
Item	n	Increased	Reduced	Not changed
Stein and Shurson, 2009[1]				
Growth performance				
ADG	25	1	6	18
ADFI	23	2	6	15
G:F	25	4	5	16
Carcass characteristics				
Carcass yield	18	0	8	10
Backfat depth	15	0	1	14
Percentage of fat-free lean	14	0	1	13
Iodine value	8	7	0	1
Published studies after 2009[2]				
Growth performance				
ADG	16	0	6	10
ADFI	16	2	6	8
G:F	16	2	5	9
Carcass characteristics				
HCW	17	0	9	8
Carcass yield	17	0	9	8
Backfat depth	17	0	5	12
Percentage of fat-free lean	14	3	0	11
Iodine value	15	15	0	0

[1] 25 experiments reviewed by Stein and Shurson (2009).

[2] Data from experiments by Bergstrom et al. (2009), Xu et al. (2010a,b), Leick et al. (2010), Cromwell et al. (2011), Dahlen et al. (2011), Lee et al. (2011), Salyer et al. (2012), McClelland et al. (2012), Hilbrands et al. (2013), Weber et al. (2013), Ying et al. (2013), Hardman (2013), Graham et al. (2014a, b), and Davis et al. (2015).

Effects on carcass characteristics

A summary of 17 experiments (published from 2009 to 2015) that determined the effects of dietary DDGS on carcass characteristics of growing-finishing pigs is presented in Table 1.4. Results are in agreement with studies summarized by Stein and Shurson (2009). Carcass yield and HCW decreased in 53% of these experiments, while no change was reported in the other 47% of experiments. A reduction in HCW is likely the consequence of reduced final BW of pigs resulting from decreased ADFI and ADG

(Hilbrands et al., 2013; Hardman, 2013). In addition, DDGS contains about 3 times more NDF content than corn (Xu et al., 2010a), and this elevated dietary fiber content may have resulted in the decreases in carcass yield observed in some experiments because of the increased gut fill and increased intestine and visceral organ weight (Kass et el., 1980; Agyekum et al., 2012; Graham et al., 2014a). Backfat thickness (10^{th} rib backfat or last rib backfat) was not affected in 29% of the experiments, but was reduced in the remaining studies. It is possible that the reduced lipid intake (as the consequence of oil extraction in producing DDGS) and the relatively low digestibility of lipid in DDGS, as well as decreased dietary energy available for adipose tissue accretion, contributed to reduced backfat thickness reported in some studies. In 3 of the 14 experiments, an improvement in the percentage of carcass fat-free lean was reported, while no effects of DDGS inclusion were observed in the other 11 studies. These data suggest that the DDGS diets fed in recent studies may have had sufficient dietary digestible AA for lean tissue development, which may be the benefit from our improved understanding and prediction of AA digestibility differences among DDGS sources. Finally, in all of the 15 experiments where IV of pork fat depots were measured, greater IV was observed when increasing dietary levels of DDGS were fed to growing-finishing pigs. Elevated carcass fat IV is a common measure used to indicate reduced pork fat quality.

Effects on pork fat quality

Pork fat quality refers to the visual and textural aspects of carcass fat tissue, such as color, firmness, and presence of unusual flavors (Xu, 2007). Color is an important physical characteristic of pork fat quality to meet export specifications, especially for markets like Japan where bright white color is preferred (Hugo and Roodt, 2007). More

importantly, firmness of pork fat is a major concern for pork processors because soft fat is often associated with increased slicing difficulties in bacon manufacturing, undesirable oily appearance, and high susceptibility to oxidative rancidity of pork products (NPPC, 2000; Benz et al., 2010). Reductions in pork fat quality have been reported extensively when DDGS was added in growing-finishing diets (Xu et al., 2010a,b; Benz et al., 2010; Graham et al., 2014a,b), which is caused by the concentration and composition of the corn oil present in DDGS sources.

Impact of DDGS oil content on lipid metabolism in adipose tissue and effects on pork fat quality

Lipid accretion in adipose tissue of pigs occurs primarily from two pathways: direct deposition of digested and absorbed dietary FA and *de novo* synthesis of FA using excess glucose and protein (Dodson et al., 2010). The balance between the two pathways can be modified by the lipid concentration in diets fed to pigs. Increased dietary fat intake inhibits *de novo* FA synthesis and favors direct deposition of dietary fat (Farnworth and Kramer, 1987). Xu (2007) summarized 2 possible mechanisms for the inhibitory effect of dietary fat on lipogenesis: limitation of lipogenic enzyme activity, and inhibition of insulin action that stimulates lipogenesis in adipose tissue and liver. As described in previous sections, DDGS has traditionally contained more than 10% oil and thus, leads to greater dietary lipid intake of pigs fed diets containing high dietary levels of DDGS compared with those fed corn and soybean meal based diets. Therefore, FA composition of the deposited fat will be reflected primarily by the FA composition of corn oil in DDGS, particularly linoleic acid. Fatty acid profile of DDGS sources reported in recent studies (Benz et al., 2010; Graham et al., 2014a, b; Davis et al., 2015) consists of about

17.3% saturated FA (**SFA**), 27.3% monounsaturated FA (**MUFA**), and 55.4% polyunsaturated FA (**PUFA**), including 53.8% linoleic acid (C18:2). As a result, it can be expected that pigs fed diets with greater levels of DDGS will have a higher concentration of PUFA, especially C18:2 content, in carcass fat depots. Benz et al. (2010) suggested that for each 10% increase in DDGS content in finishing diets, C18:2 and PUFA content increased 1.68 and 1.78%, respectively, regardless of fat depots, and IV of backfat, jowl fat, and belly fat increased by 2.3, 1.6, and 2.2 g/100 g, respectively.

Increased unsaturated FA in carcass fat is responsible for poor pork fat quality. The concentration of unsaturated FA in pork fat is correlated negatively with fat firmness. Whittington et al. (1986) reported that increased dietary C18:2 content linearly reduced backfat firmness, measured as the force required to penetrate the tissue. Similarly, Cromwell et al. (2011) determined the belly flex (lower lateral and higher vertical flex indicated softer and more flexible belly) of pigs fed different dietary levels of DDGS, and found that the lateral flex measurement decreased linearly, and vertical flex increased linearly as the dietary inclusion of DDGS increased from 0 to 45%. Furthermore, high PUFA content often leads to undesirable yellow color of carcass fat, primarily due to its relatively high concentration of fat-soluble pigments (carotenoids; Xu, 2007). Finally, unsaturated pork fat is more susceptible to lipid peroxidation and results in deteriorated meat color, flavor, texture, and nutritive value (Xu, 2007).

Based on this evidence, it is reasonable to expect that the negative effect of feeding DDGS on pork fat quality may be reduced as more corn oil is extracted during the DDGS production process (Graham et al., 2014b). However, the magnitude of this improvement has not been determined. Moreover, digestibility of oil that is contained in

DDGS is highly variable among sources, and it is likely that the unextracted portion of corn oil is less digestible for pigs. Kerr et al. (2013) evaluated 15 sources of DDGS with variable oil content and observed that the ATTD of EE ranged from 52.7 to 81.2%, and appeared to be lower when concentration of EE is low. Therefore, the effects of feeding reduced-oil DDGS on pork fat quality need to be further evaluated.

Iodine value

Iodine value is a common measurement of the ratio of unsaturated to saturated FA in a lipid. It is directly determined by measuring the amount of iodine (g) absorbed by double bonds of FA in 100 g of fat (Averette Gatlin et al., 2003). Therefore, IV has been used as the unofficial "standard" indicator for fat firmness in the pork industry (increasing IV indicates softer carcass fat). Although iodine value can be measured using chemical analysis, the skill and time required for this analysis has resulted in limited use of this procedure for assessing pork fat quality (DeRouchey et al., 2010). As an alternative, equations have been developed to calculate IV from analyzed FA profile. The equation from AOCS (1998) has been most commonly used in the U.S. pork industry: IV (g/100g) = [C16:1] × 0.95 + [C18:1] × 0.86 + [C18:2] × 1.732 + [C18:3] × 2.616 + [C20:1] × 0.785 + [C22:1] × 0.723, where brackets indicate concentration of the FA.

The relationship between adding DDGS in growing-finishing diets and increased IV and softness of carcass fat has been well established in many studies (Table 1.4). As a result, some packing plants have developed specific recommendations regarding the maximum use of DDGS in finishing diets (DeRouchey et al., 2010). In addition, many pork packers and processors have set their maximum acceptance of IV in carcass fat depots. For example, Madsen et al. (1992) recommended that IV should be less than 70

g/100g in order to maintain high pork fat quality, while Boyd et al. (1997) suggested 75 g/100g as the threshold.

1. Differences in IV among carcass fat depots

Location of the fat depot may influence the IV reported (DeRouchey et al., 2010). Evans et al. (2009) showed that pigs fed corn and soybean meal diets with added fat had greater average IV (g/100g) in jowl fat (64.51) than in belly and backfat (60.97 and 58.26, respectively). Xu et al. (2010a) observed a greater average IV of belly fat than backfat (67.11 vs. 65.67, respectively) for pigs fed increasing levels of DDGS from 0 to 30%. Harris (2014) also suggested that jowl fat (69.4) had higher IV than backfat (66.6) and belly fat (62.5) in pigs fed 40% DDGS when using various DDGS diet feeding strategies (withdrawing or "step-down" DDGS) and immunocastration treatments. However, Leick et al. (2010) reported that pigs fed increasing DDGS content (0 to 60%) had an average belly fat IV greater than jowl fat (90.6 vs. 86.7, respectively), which was opposite to the results reported by Evans et al. (2009) and Harris (2014).

Several mechanisms have been proposed regarding the variation in FA profile among pork fat depots. One possible reason is the different rates of adipose tissue development. Late-developing tissues may be more saturated compared with early-developing tissues, because pigs have greater energy intake, relative to requirements for lean tissues accretion, during the later stages of growth and consequently, more excess energy is available for *de novo* synthesis of FA (Lizardo et al., 2002). According to the fat accretion patterns (from the distal end of the body toward the visceral cavity) of food animals characterized by Hammond (1932), pigs tend to deposit lipids earlier in jowl compared with loin and belly regions, which is in the agreement with greater IV observed

in jowl fat. Another possible factor is the difference in lipogenic activity at the various adipose tissues (Xu et al., 2010a). Mourot et al. (1995) showed that, among the 3 fat depots, jowl fat had significantly lower activities of acetyl-CoA-carboxylase, malic enzyme, and glucose-6-dehydrogenase (lipogenic enzymes) during the growing-finishing period. Therefore, FA deposition in jowl fat is caused more by the direct deposition of dietary lipids, which were predominately unsaturated fatty acids.

Ideally, IV should be measured from belly fat, because belly is the most valuable segment of the carcass and used to process into bacon. However, it is difficult to collect samples of belly fat for analysis without compromising the value of this primal cut. Studies (Evans et al., 2009; Leick et al., 2010; Estrada, 2013; Villela et al., 2015) have been conducted to predict IV of belly fat from other fat depots. Villela et al. (2015) showed that jowl fat IV can be used to predict IV of backfat ($r = 0.84$), but it is less reliable for predicting IV of belly fat ($r = 0.60$). Evans et al. (2009) also suggested that IV of backfat and LM intramuscular fat are better indicators of belly IV compared with jowl fat (Evans et al., 2009). Therefore, an increasing number of packing plants are currently using backfat samples for pork fat quality assessment.

2. Strategies to manage pork fat IV

Several feed formulation and feeding strategies have been developed to help pork producers to maximize the utilization of DDGS in growing-finishing diets while maintaining acceptable carcass fat IV and pork fat quality. First, up to 70% reduction in C18:2 content in pork fat depots can be achieved in 2 weeks following a withdrawal of high-oil DDGS from the diet, and 100% reduction may be realized in about 6 to 8 weeks (Xu et al. 2010b). Therefore, reducing unsaturated FA intake by withdrawing or

gradually reducing DDGS inclusion from diets for as little as 3 weeks prior to harvest is effective in decreasing IV and improving firmness of fat depots (Jacela et al., 2009; Xu et al., 2010b; Hilbrands et al., 2013). Second, conjugated linoleic acid (**CLA**), a group of positional and geometric isomers of C18:2, decreases the activity of Δ^9 desaturase in adipose tissue (White et al., 2009), and consequently has the potential to increase the degree of saturation in carcass fat. Iodine value in backfat and belly fat (White et al., 2009) and in jowl fat (Rickard et al., 2012) were reduced significantly when 0.6% CLA was added in growing-finishing diets. Studies by Mourot et al. (1994) and Schieck et al. (2010) showed that adding crude glycerol to corn and soybean meal based diets decreased IV and improved firmness of carcass fat. However, this improvement was not observed when pigs were fed diets containing 20% DDGS (Duttlinger et al., 2012) or 40% DDGS (Villela et al., 2014). Third, reducing carcass fat IV can be achieved when including more saturated FA sources (e.g. tallow, palm oil) in diets containing DDGS, but the effectiveness of using this strategy has been inconsistent among researchers. Lee et al. (2013) showed that backfat and belly fat IV were unaffected in pigs fed 30% DDGS diets with 3% beef tallow or 3% palm kernel oil compared with pigs fed corn and soybean meal control diets, while Davis et al. (2015) indicated that adding 5% tallow to 30% DDGS diets reduced IV for belly fat, but not for backfat. Furthermore, nutritionists can manage pork fat quality by formulating diets based on IV product (**IVP**), which is a composite value of FA composition and quantity of dietary lipid present in fat sources (IVP = dietary IV × % dietary lipids × 0.10; Harris, 2014). However, Benz et al. (2011a) measured the backfat and jowl fat IV of pigs fed diets with increasing levels of IVP by adding extruded expelled soybean meal, DDGS, or choice white grease. Their results

suggested that dietary IVP may not adequately predict carcass fat IV when diets were formulated from different fat sources and with various degrees of FA unsaturation, and instead, dietary C18:2 concentration was a better indicator of carcass fat IV. Finally, including alternative cereal grains with lower linoleic acid content to substitute corn in diets with DDGS may help to control carcass fat IV (USGC, 2012). Studies conducted in western Canada have shown that IV of pork fat in pigs fed wheat, barley, and canola meal based diets is lower compared with pigs fed corn-soybean meal based diets (Beltranena et al., 2009). Benz et al. (2011b) also suggested that pigs fed sorghum-based diets had reduced backfat and jowl fat IV compared with pigs fed corn-based diets.

3. Prediction of carcass fat IV

Empirical equations have been developed to predict carcass fat IV based on the source and composition of dietary lipid. A summary of prediction equations for backfat, belly, and jowl fat IV is presented in Table 1.5. Dietary C18:2 concentration and dietary IVP were used in studies (Boyd et al., 1997; Bergstrom et al., 2010; Benz et al., 2011a) as single predictors, because of their highly profound effects on FA composition of carcass fat. Madsen et al. (1992) and Kellner (2014) proposed another set of equations that account for feed intake, using daily intake of C18:2 or IVP as predictors. Additionally, Cromwell et al. (2011) and Estrada (2013) indicated that the dietary inclusion level of DDGS was correlated closely with carcass fat IV. However, use of equations based on the percentage of DDGS in diets is questionable because of the variability in oil concentration among DDGS sources.

In general, all of these equations have focused on the effects of dietary lipid on FA composition of carcass fat, whereas other factors such as dietary energy concentration

and feeding strategies (e.g. withdraw or "step-down" DDGS inclusion) may also affect lipid metabolism and FA composition of pork fat depots. Therefore, it is logical to argue that growth performance responses, carcass composition, and dietary energy content should be considered in the IV prediction. Estrada (2013) added carcass characteristics (final BW, carcass yield, and last-rib backfat depth) as additional predictor variables to carcass fat IV prediction equations, but found little or no improvement in R^2 compared with using dietary DDGS inclusion level as the single predictor. More recently, Paulk et al. (2015) conducted a meta-analysis that included 5 groups of predictor variables: dietary lipid composition, feeding days, ME or NE content of diets, live performance criteria, and carcass composition. Three new equations with high R^2 (> 0.92) were developed for the predictions of backfat, belly, and jowl fat IV in this meta-analysis.

Table 1.5. Summary of selected regression equations developed to predict jowl, back, or belly fat iodine value. Adapted from Harris (2014).

Study	Jowl	Back	Belly	Equation	*P*	R^2
Madsen et al., 1992		X[1]		47.1 + 0.14 × IVP[2] intake/d	-	0.86
Boyd et al., 1997		X		42.4 + 0.315 × Diet IVP	-	-
Bergstrom et al., 2010	X			61.95 + 0.15 × Diet IVP	-	0.45
Bergstrom et al., 2010		X		57.89 + 0.18 × Diet IVP	-	0.58
Bergstrom et al., 2010			X	58.85 + 0.16 × Diet IVP	-	0.78
Cromwell et al., 2011		X		64.5 + 0.432 × DDGS in diet, %	-	0.92
Benz et al., 2011a	X			0.247 × Diet IVP + 56.479	0.24	0.32
Benz et al., 2011a		X		0.2715 × Diet IVP + 51.946	0.44	0.16
Benz et al., 2011a	X			10.111 × Diet C18:2n6 + 47.469	<0.01	0.90
Benz et al., 2011a		X		14.324 × Diet C18:2n6 + 35.458	<0.03	0.73
Estrada, 2013	X			72.99 + 0.24 × DDGS in diet, %	-	0.81
Estrada, 2013	X			64.54 + 0.27 × Diet IVP	-	0.81
Estrada, 2013		X		70.06 + 0.29 × DDGS in diet, %	-	0.81
Estrada, 2013		X		60.13 + 0.27 × Diet IVP	-	0.81
Estrada, 2013			X	67.35 + 0.26 × DDGS in diet, %	-	0.75
Estrada, 2013			X	58.32 + 0.25 × Diet IVP	-	0.74
Kellner, 2014	Average of 3 depots			58.102 + 0.2149 × Diet IVP	<0.01	0.93
Kellner, 2014	Average of 3 depots			58.566 + 0.1393 × C18:2 intake/d, g	<0.01	0.94
Paulk et al., 2015[3]	X			85.50 + (1.08 × I EFA) + (0.87 × F EFA) - (0.014 × I d) - (0.050 × F d) + (0.038 × I EFA × I d) + (0.054 × F EFA × F d) - (0.0066 × I NE) + (0.071× I BW) - (2.19 × ADFI) - (0.29 × BF)	-	0.93
Paulk et al., 2015[3]		X		84.83 + (6.87 × I EFA) - (3.90 × F EFA) - (0.12 × I d) - (1.30 × F d) - (0.11 × I EFA × F d) + (0.048 × F EFA × I d) + (0.12 × F EFA × F d) - (0.0060 × F NE) + (0.0005 × F NE × F d) - (0.26 × BF)	-	0.95
Paulk et al., 2015[3]			X	106.16 + (6.21 × I EFA) - (1.50 × F d) - (0.11 × I EFA × F d) - (0.012 × I NE) + (0.00069 × I NE × F d) - (0.18 × HCW) - (0.25 × BF)	-	0.94

[1] X indicates the fat depot for which the prediction equation is developed.

[2] Iodine value product = dietary IV × % dietary lipids × 0.10

[3] I = initial diet, F = final diet, d = duration of diet fed, EFA = essential fatty acids (C18:2 and C18:3; %), BW = body weight (kg), NE = net energy (kcal/kg), HCW = hot carcass weight (kg), and BF = backfat depth (mm).

In contrast to the empirical models described above, more mechanistic nutritional models have also been proposed by a European research team (Lizardo et al., 2002) to study the effect of diet composition on lipid deposition and FA composition in pork carcasses. A basic growth model has been used to determine the protein and lipid deposition of pigs by estimating the feed intake (energy intake), upper limit to protein deposition (PD_{max}), and the minimum ratio between lipid and protein mass (minLP). This

model assumes that energy intake in excess of maintenance will be first used for protein deposition, but calculation of this portion of energy utilization needs to account for the PD_{max} and minLP during protein deposition (Lizardo et al., 2002). As a results, a second model was subsequently developed to partition fat deposition between direct deposition from dietary lipid (80%) and *de novo* lipogenesis (20%), and to further partition the *de novo* synthesized FA into 24% palmitic acid, 19% stearic acid, and 54% oleic acid (Lizardo et al., 2002). Based on this model, FA profile of adipose tissues can be theoretically calculated. However, this model has not been widely applied in the U.S. because the variables used in this model still requires refinement to include other factors such as the effect of enzymatic activity on lipid metabolism.

Feeding wheat middlings and DDGS to growing-finishing pigs

Wheat middlings (**WM**) is a by-product of the wheat milling industry and consists of fine particles of wheat bran, wheat shorts, wheat germ, wheat flour and the "tail of the milling" (Erickson et al., 1985). In recent years, there has been a steady increase in the use of WM as an alternative feed ingredient in grower-finisher swine diets to reduce feed cost. Wheat middlings contain a greater concentration of protein and fiber than corn. The NRC (2012) suggests that the average CP and NDF content of WM are 15.8 and 35.0%, respectively, which are about 91.3 and 283.9%, respectively, greater than CP and NDF content of corn. Similar to other high-fiber ingredients, variability in nutrient composition exists among WM sources. Cromwell et al. (2000) compared the nutrient profile of 14 sources of WM produced in 13 states and showed that CP content varied from 14.6 to 17.6%, but NDF content had greater variability ranging from 29.9 to 43.9%. Results from this study also suggested that bulk density can be used as an important indicator of WM

quality, because heavier WM sources likely have greater proportion of flour attached to wheat bran particles, resulting in increased protein content and feeding value (Cromwell et al., 2000).

Variation in energy content has also been a challenge for nutritionists to optimize the use of WM in growing-finishing diets. Concentrations of GE, DE, and ME in a WM source reported by Pals and Ewan (1978) were 4,550, 3,470, and 3,340 kcal/kg DM, respectively, and the NE content determined by comparative slaughter method was only 27% (910 kcal/kg DM) of the ME value. Patience et al. (1977) estimated the energy digestibility of 2 batches of Canadian wheat shorts, which showed a large difference between their DE values (2,900 vs. 3,440 kcal/kg). Later, Erickson et al. (1985) conducted an energy balance study with a WM source in pelleted diets. Estimated ME content of this source was 2,990 kcal/kg, which is about 10.5% less than the values reported by Pals and Ewan (1978). Surprisingly, limited data have been published regarding the ME and NE concentrations of WM during the last 30 years. However, in 2013, Stewart et al. measured the NE of a WM source using the comparative slaughter method and reported that the NE content of WM were similar in growing and finishing phases (959 and 1,015 kcal/kg, respectively). These values were slightly greater than those determined by Pals and Ewan (1978), but were only about 50% of the NRC (2012) recommended NE (2,113 kcal/kg) for WM. In general, WM contains lower ME and NE concentrations compared with corn, and the variability in energy content of WM, especially NE, may be greater than that of DDGS. Therefore, further research is needed to assess the accuracy of using currently published NE estimates for WM in diet formulation.

Several studies have been conducted to determine the effects of feeding WM on growth performance, carcass characteristics, and pork fat quality of growing-finishing pigs. Erickson et al. (1985) used WM to replace 0, 10, 20, and 30% of corn in diets on an equal-weight basis and showed that increasing dietary WM inclusion resulted in a linear increase in overall ADFI and decrease in G:F, but ADG and carcass composition (LMA and FFL%) were not affected. In addition, feeding the WM diets decreased loin quality by reducing the firmness and loin color score.

Asmus et al. (2011) fed diets with similar dietary ME content, but increasing NDF content by adding WM and DDGS in the formulation. No interactions between feeding DDGS and WM were observed for growth performance responses in this study. Pigs had linearly decreased ADG and G:F as the inclusion of WM increased, but ADFI was not affected. These findings indicated that ME (3,031 kcal/kg as-fed) of WM was overestimated, and pigs did not compensate for lower dietary energy content by eating more feed. Except for reducing HCW, feeding WM had no effects on the carcass measurements including backfat depth, loin depth, and percentage of carcass fat free lean. In addition, jowl fat IV was increased when DDGS or WM were included in diets, but the magnitude of increase was greater in the DDGS diets.

Salyer et al. (2012) conducted 2 experiments to evaluate the effects of feeding combinations of DDGS and WM (up to 20% of the diet) to growing-finishing pigs. Diets were not balanced for equal energy content, but were formulated on the ME basis to meet AA requirements (equal SID Lys:ME ratio). Similar to the observation reported by Asmus et al. (2011), pigs had reduced ADG and G:F, but not ADFI, when 10 or 20% WM were added in diets. Feeding the WM diets also decreased HCW, carcass yield, and

backfat depth, but improved carcass fat free lean percentage. However, inconsistent observations were observed in the 2 experiments regarding the response of pork fat quality to the dietary inclusion of WM (jowl fat IV was unaffected in Exp. 1, but was increased in Exp. 2).

In summary, feeding WM to growing-finishing pigs generally decreases growth performance and carcass yield, and may also affect pork fat quality, primarily because the high fiber concentration of WM decreases bulk density of diets and limits pig's gut capacity to maintain required energy intake. Furthermore, using ME as the basis for diet formulation may have also contributed to the negative responses of pigs fed WM in previous studies, because ME system tends to overestimate the actual energy content of high-fiber ingredients.

Summary

Corn DDGS is a high-fiber, alternative ingredient that has been extensively used in the U.S. swine industry to provide an economical source of energy, AA, and digestible P. Large variation in the chemical composition and nutrient digestibility exists among DDGS sources, and the implementation of oil extraction procedures by most ethanol plants has further increased this variability. As a consequence, reports on the energy concentrations among sources of DDGS vary widely; ME values range from 2,858 to 4,108 kcal/kg DM, and NE values range from 2,009 to 2,893 kcal/kg DM. Therefore, nutritionists are facing great challenges in using accurate nutrient and energy loading values for DDGS in the diet formulation.

Metabolizable energy is currently the most commonly adopted system in the U.S. for diet formulation, but it overestimates the available energy content of feed ingredients

that contain high levels of various types of fiber. As the use of high-fiber ingredients in swine diets continues to increase, nutritionists must formulate diets based on NE content to optimize caloric efficiency. Current methodologies to accurately determine ME and NE content of feed ingredients are rather labor-intensive, costly, and do not provide dynamic measurements for practical application. Alternative approaches such as empirical equations and commercial services have been developed for estimating ME and NE content among DDGS sources, but these energy estimates require further evaluation and validation using growth performance experiments.

Furthermore, feeding high-fiber ingredients such as DDGS and WM often results in inconsistent growth performance and carcass responses of growing-finishing pigs, which is explained mainly by the limited feed intake of pigs resulting from elevated dietary fiber content and inadequate estimation of dietary energy. In addition, reduced pork fat quality, particularly soft bellies, has been one of the biggest concerns when feeding diets containing more than 20% DDGS to growing-finishing pigs. To maintain acceptable pork fat firmness, producers have the option to use prediction equations to estimate carcass fat IV based on dietary lipid content and composition, as well as use various feeding strategies to reduce intake of unsaturated FA before harvest.

Experiments presented in this thesis determined the growth performance, carcass composition, and pork fat quality of pigs fed DDGS sources with variable oil and energy (ME and NE) concentrations (chapter 2 and 3). Observed growth responses were used to evaluate the precision and accuracy of published equations and commercial services in predicting ME and NE content of DDGS. Based on determined carcass fat IV, the study described in chapter 4 evaluated and identified the most precise and accurate IV

prediction equations for backfat, belly, and jowl fat depots. Finally, chapter 5 provides data showing the effects of feeding high-fiber ingredients (DDGS and WM), when diets are formulated on a NE basis, on the growth performance and carcass characteristics of growing-finishing pigs.

CHAPTER 2

Evaluation of ME predictions and the impact of feeding corn distillers dried grains with solubles with variable oil content on growth performance, carcass composition, and pork fat quality of growing-finishing pigs

Summary

A total of 432 pigs (initial BW: 25.8 ± 5.1 kg) were used to evaluate growth performance, carcass characteristics, and pork fat quality of growing-finishing pigs fed corn-soybean meal diets containing 40% distillers dried grains with solubles (DDGS) with variable ether extract (EE) content, but similar predicted ME concentration (3,232 to 3,315 kcal/kg predicted by a commercial service). Pigs were blocked by initial BW, and within blocks, pens were allotted randomly to 1 of 4 dietary treatments (9 pigs/pen, 12 replicates/treatment) in a 4-phase feeding program (26 to 50 kg, 50 to 75 kg, 75 to 100 kg, and 100 to 120 kg BW). Dietary treatments consisted of: 1) corn-soybean meal (CON), 2) 40% low-oil DDGS (5.9% EE; LOW), 3) 40% medium-oil DDGS (9.9% EE; MED), and 4) 40% high-oil DDGS (14.2% EE; HIGH). Diets contained similar concentrations of standardized ileal digestible AA and standardized total tract digestible P within each phase. Overall, ADFI of pigs fed CON was greater ($P < 0.05$) than MED and HIGH, and tended ($P < 0.10$) to be greater than LOW. No difference in ADFI was observed among DDGS treatments. Average daily gain of pigs fed LOW, MED, and HIGH was not different, but was less ($P < 0.05$) than pigs fed CON. However, pigs fed LOW had reduced ($P < 0.05$) G:F compared with the other treatments. Pigs fed CON had greater ($P < 0.05$) HCW, carcass yield, and LM area than those fed the DDGS diets, but there were no differences among DDGS treatments. No treatment differences were observed for backfat depth and percentage of carcass fat-free lean. Back, belly, and jowl fat iodine

value of pigs fed LOW and MED was less ($P < 0.01$) than in pigs fed HIGH, but was greater ($P < 0.01$) than in pigs fed CON. Based on observed G:F, dietary ME content of LOW was less than MED, HIGH, and CON diets, indicating a slightly overestimation of ME prediction for low-oil DDGS source from the commercial report and Anderson et al. (2012) equations. In conclusion, including 40% DDGS in corn-soybean meal based diets negatively impacts the growth performance of growing-finishing pigs. Reduced EE content of DDGS sources did not affect ADG, ADFI, and carcass composition, but improved pork fat quality. However, current ME predictions need to be refined for more accurate estimation of ME content for low-oil DDGS sources for swine.
Key words: distillers dried grains with solubles, ME prediction, growing-finishing pigs

Introduction

Corn dried distillers grains with solubles (**DDGS**) is a widely used alternative feed ingredient in swine diets, with an ME content comparable to corn (Stein and Shurson, 2009). However in recent years, most ethanol plants have been extracting corn oil thereby producing reduced-oil DDGS. Oil extraction has resulted in large variability in ether extract (**EE**; 5 to 12%) and ME content among DDGS sources (Kerr et al., 2013), which may increase the risk of inaccurate diet formulations. Reduction in oil content was expected to reduce ME content of DDGS, whereas Kerr et al. (2013) showed that EE content was a poor predictor of ME content.

Prediction equations (Pedersen et al., 2007; Anderson et al., 2012; Kerr et al., 2013) and commercial estimates (ILLUMINATE®; Nutriquest, Mason City, IA) have been developed to predict ME content of DDGS sources based on chemical composition. Cross-validation of published equations by Urriola et al. (2014) indicated that using the

combination of equations from Anderson et al. (2012): DE = -2,161 + (1.39 × GE) – (20.7 × NDF) – (49.3 × EE) and ME = -261 + (1.05 × DE) – (7.89 × CP) + (2.47 × NDF) – (4.99 × EE) generated the most accurate and precise ME estimates for DDGS. However, these estimates require validation using growth performance data.

Feeding diets containing traditional high-oil (> 10% EE) DDGS reduces belly and pork fat firmness because corn oil contains a high concentration of PUFA (Stein and Shurson, 2009; Xu et al., 2010a; Davis et al., 2015). Pork fat quality may be improved by feeding DDGS sources with less oil content, but limited data are available to show the magnitude of this improvement. Therefore, the objectives of this study were to determine the effects of feeding 40% DDGS, and the impact of variable oil content of DDGS on the growth performance, carcass traits, and pork fat quality of growing-finishing pigs, and to evaluate the ME predictions for DDGS using Anderson et al. (2012) equations and ILLUMINATE®.

Materials and methods

All experimental procedures in this study were approved by the University of Minnesota Institutional Animal Care and Use Committee (St. Paul, MN).

Animals and housing

Pigs (416 barrows and 16 gilts; initial BW: 25.8 ± 5.1 kg) were blocked by initial BW and allotted to 12 blocks (4 pens/block; 9 pigs/pen). Sex ratio (8 barrows and 1 gilt in blocks 1 to 4) was balanced among pens, but not among all blocks. Pigs were housed in an environmentally controlled grower-finisher facility at the University of Minnesota West Central Research and Outreach Center (Morris, MN). Each pen (1.60 × 4.5 m) consisted of completely slatted, concrete floors, and was equipped with a nipple waterer

and 1 single-sided self-feeder with 4 feeding spaces. Room temperature of the facility was maintained at about 20°C. Pigs were allowed ad libitum access to feed and water throughout the experiment. Pigs that showed signs of poor health were treated individually with appropriate medication or removed from the experiment.

Diets and experimental design

ILLUMINATE® is a proprietary commercial service that uses chemical composition of DDGS sources and prediction equations to estimate DE, ME, NE, and standardized ileal digestible (**SID**) AA content of the majority of DDGS sources produced by ethanol plants in the U.S. ILLUMINATE® service served as a tool to select 3 sources of DDGS with variable oil content, but similar ME concentration, for use in this study. These DDGS sources contained: 1) 5.87% EE and predicted ME of 3,258 kcal/kg for low-oil DDGS, 2) 9.85% EE and predicted ME of 3,315 kcal/kg for medium-oil DDGS, and 3) 14.23% EE and predicted ME of 3,232 kcal/kg for high-oil DDGS. All sources of DDGS, corn, and soybean meal were obtained in single lots, and samples were obtained for chemical analyses (Table 2.1). Results of these analyses were used in diet formulation. Gross energy content of DDGS was determined using bomb calorimetry at the University of Minnesota (Model 1281, Parr Instrument Co., Moline, IL). The estimated ME concentrations for each DDGS source were calculated using a sequential combination of equations from (Anderson et al., 2012): DE = -2,161 + (1.39 × GE) – (20.7 × NDF) – (49.3 × EE) and ME = -261 + (1.05 × DE) – (7.89 × CP) + (2.47 × NDF) – (4.99 × EE). Selection of these equations was based on the results from a cross-validation research conducted by Urriola et al. (2014). Comparison of observed overall G:F responses among dietary treatments were used to evaluate the ME estimates from ILLUMINATE®,

Anderson et al. (2012) equations, and NRC (2012).

Pens of pigs were allotted randomly to 1 of 4 dietary treatments (Table 2.2 and 2.3) in a 4-phase feeding program (25 to 50 kg, 50 to 75 kg, 75 to 100 kg, and 100 to 120 kg BW for phase 1 to 4, respectively). Phases were switched when average BW of pigs in the pen reached the targeted starting BW ± 2.3kg of the subsequent phase. Dietary treatments consisted of: 1) corn-soybean meal (**CON**), 2) CON with 40% low-oil DDGS (**LOW**), 3) CON with 40% medium-oil DDGS (**MED**), and 4) CON with 40% high-oil DDGS (**HIGH**). Diets were not adjusted for dietary ME content, but were formulated to contain similar concentrations of SID AA and standardized total tract digestible (**STTD**) P within each phase. The coefficients for AA digestibility of DDGS sources were obtained from equations reported by Almeida et al. (2013) based on analyzed AA composition. Energy values and coefficients for SID AA and STTD P of corn and soybean meal were obtained from NRC (2012). All diets met or exceeded the nutrient requirements of growing-finishing pigs from the NRC (2012) model based on growth performance and lean growth rate of pigs observed in a previous experiment (Song et al., 2013) conducted in the same facilities. During the 2 weeks before the experiment commenced, pigs were double stocked (18 pigs/pen) in one side of the finisher facility and fed a common corn-soybean meal diet until the other side of the facility was prepared for the experiment. As a result, experimental diets were offered initially to pigs at an average BW of 39.3 kg, even though phase 1 diets were formulated for pigs with BW from 25 to 50 kg. Body weight of individual pigs and feed disappearance in each pen were measured every other week to calculate ADG, ADFI, and G:F. Feed samples were obtained and frozen (-20°C) when

each batch of feed was mixed, and 4 samples of each treatment (1 sample from each of the 4 phases; 16 samples total) were selected randomly for analysis of nutrient composition.

In the formulation of phase 1 diets, an extra 1% limestone was mistakenly included at the expense of corn in the LOW diet, which resulted in increased dietary Ca concentration and elevated Ca:P ratio. However, comparison among pigs fed LOW and other DDGS treatments in phase 1 showed no negative effect of this flawed diet formulation on pig growth performance.

Carcass measurements

Pigs were divided into 2 groups (pigs from block 1 to 6 with higher initial BW were in group 1 and pigs from block 7 to 12 with lighter initial BW were in group 2) and harvested at 2 times that were 8 d apart. For each group, when pigs reached market weight, backfat (**BF**) depth and loin muscle area (**LMA**) were measured between the 10th and 11th ribs using an ALOKA 500V real-time ultrasound machine (Corometrics Medical Systems, Wallingford, CT) by a certified technician. After ultrasound measurements were obtained, final BW was determined and pigs were tattooed individually and transported to a commercial abattoir (Hormel Foods; Austin, MN). Hot carcass weight was recorded on the harvest line immediately after evisceration and was used to calculate carcass yield using: carcass yield, % = HCW/Final BW × 100. Carcasses of 11 pigs were trimmed during USDA inspection, so their HCW were removed from the dataset. Percentage of carcass fat free lean (**FFL%**) was calculated using: FFL% = {[2.620 + (0.456 × sex of pig) – (3.358 × 10th rib backfat depth, cm) + (0.306 × 10th rib LMA, cm^2) + (0.401 × HCW, kg)]/HCW, kg} × 100, where sex of pig is defined as barrow = 1 and gilt = 2 (NPPC, 2000).

Samples of back, belly, and jowl fat were collected from 2 barrows/pen with final BW closest to the pen average BW. All fat samples were collected from the left side of the carcasses. Backfat samples (n = 96) were collected from the midline opposite the last rib and included all 3 fat layers. Belly fat samples (n = 96) were collected from the midline opposite the last rib on the teat side of the belly, and jowl fat samples (n = 96) were obtained from the anterior tip of the jowl. One jowl fat sample was lost because the carcass was trimmed during USDA inspection. Samples were packaged in Whirlpac® sample bags, stored in a cooler with dry ice, and delivered to the University of Minnesota Swine Nutrition Laboratory within 2 h after collection. All fat samples were frozen with dry ice during transportation to the University of Missouri Agricultural Experiment Station Chemical Laboratory (**AESCL**; Columbia, MO) for analysis of fatty acid profile.

Chemical analysis

Five feed ingredient samples (3 sources of DDGS, 1 source of corn, 1 source of soybean meal) and 16 complete diets were analyzed for nutrient composition at AESCL. Standard procedures of AOAC (2006) were followed for analysis of moisture (Method 934.01), CP (Method 990.03), EE (Method 920.39), crude fiber (Method 978.10), ADF (Method 973.18), NDF (Holst, 1973), total dietary fiber (**TDF**; Method 985.29), Ca and P (Method 985.01), AA profile (Method 982.30), and starch content (AACC, Approved Methods, No. 76-13).

Fatty acid profile (Method 996.06; AOAC 2006) was analyzed at AESCL for the backfat (n = 96), belly fat (n = 96), and jowl fat (n = 95) samples. Iodine value (**IV**) was calculated using the following equation (AOCS, 1998): IV = [C16:1] × 0.95 + [C18:1] × 0.86 + [C18:2] × 1.732 + [C18:3] × 2.616 + [C20:1] × 0.785 + [C22:1] × 0.723, where

brackets indicate concentration.

Statistical analysis

All analyses were conducted using the MIXED procedure (SAS Inst. Inc., Cary, NC) in a randomized complete block design. Pen served as the experimental unit for all data analyses. Growth performance data of each phase were analyzed, and overall ADFI, ADG, and G:F were generated using a statistical model that included dietary treatment, phase, and dietary treatment × phase interaction as fixed effects and block as a random effect with repeated measures in time (phase). For analysis of carcass characteristics, dietary treatment was a fixed effect, block was a random effect, and final BW was used as covariate for BF depth, LMA, and percentage of FFL%, if the effect of covariate was significant ($P < 0.05$). The effect of gender in analyses of carcass traits was ignored because of the limited number of gilts (n = 16) in the study. A split plot design was used in the analysis of fatty acid profile for pork fat samples, with diet as the whole plot and carcass fat depot as the subplot. The diet × depot interaction was also included in the final statistical analysis. Means were reported as least-squares means and were separated by the PDIFF option when $P < 0.05$, and trends are reported when $0.05 < P < 0.10$.

Results

Growth performance and carcass composition

During the feeding period, 8 pigs (1, 2, 2, and 3 pigs from CON, LOW, MED, and HIGH treatments, respectively) were removed from the study due to poor health or death. For the overall feeding period, ADFI of pigs fed CON was greater ($P < 0.05$) than MED and HIGH, and tended ($P < 0.10$) to be greater than LOW (Table 2.4). However, no difference was observed in ADFI among pigs fed LOW, MED, and HIGH. No diet ×

phase interaction was observed for ADFI, but there was a trend ($P = 0.062$) for a diet × phase interaction for ADG. In phase 1, pigs fed CON had greater ($P < 0.05$) ADG than pigs fed diets containing DDGS. In phase 2, pigs fed CON had greater ($P < 0.05$) ADG than pigs fed MED and HIGH, but not those fed LOW, and no difference in ADG was observed among pigs fed LOW, MED, and HIGH. In phase 3, pigs fed CON had higher ($P < 0.05$) ADG than pigs fed LOW and HIGH, but not for pigs fed MED, and no difference was found among LOW, MED, and HIGH. In phase 4, ADG was not different among dietary treatments. Overall, ADG among pigs fed LOW, MED, and HIGH was not different, but was less ($P < 0.05$) than that of pigs fed CON. There was a trend ($P = 0.061$) for a diet × phase interaction for G:F. In phase 1, pigs fed CON had higher ($P < 0.05$) G:F than pigs fed diets containing DDGS. In phase 2 and 3, no difference in G:F was observed among treatments. In phase 4, G:F of pigs fed LOW was not different from pigs fed CON and MED, but was lower ($P < 0.05$) than HIGH, and no difference in G:F was observed among pigs fed CON, MED, and HIGH. Overall, pigs fed LOW had slightly reduced ($P < 0.05$) G:F compared with pigs fed CON, MED, and HIGH, but no differences were observed among CON, MED, and HIGH dietary treatments.

Pigs fed CON had greater ($P < 0.01$) HCW, carcass yield, and LMA than pigs fed LOW, MED, and HIGH, but there were no differences among pigs fed the 3 diets containing DDGS (Table 2.5). No treatment differences were observed for BF depth and percentage of carcass FFL%.

Pork fat quality

An interaction of dietary treatment × fat depot was observed ($P < 0.01$) for linoleic acid (C18:2) concentration (Table 2.6). In all 3 fat depots, pigs fed CON had a

lower ($P < 0.01$) C18:2 content than pigs fed diets containing DDGS. Concentration of C18:2 in the 3 fat depots of pigs fed LOW and MED was similar, but less ($P < 0.01$) than those fed HIGH. For pigs fed CON, jowl fat contained a greater ($P < 0.05$) concentration of C18:2 relative to belly fat, and C18:2 content of BF was not different compared with the two other depots. However, BF of pigs fed DDGS diets had a greater ($P < 0.01$) C18:2 concentration compared with other fat depots, but no differences were observed between belly and jowl fat.

There was a dietary treatment × fat depot interaction ($P < 0.01$) for the analysis of SFA content (Table 2.6). For all 3 fat depots, pigs fed CON had a greater ($P < 0.01$) concentration of SFA than pigs fed LOW, MED, and HIGH. The SFA concentration in BF and belly fat of pigs fed LOW and MED was similar, but were greater ($P < 0.05$) than that of pigs fed HIGH. However, in jowl fat, concentration of SFA of pigs fed LOW was not different compared with those fed MED, but was greater ($P < 0.05$) than HIGH, and no differences were observed among pigs fed MED and HIGH. For pigs fed CON, SFA concentration in BF was greater ($P < 0.01$) than in belly and jowl fat, and SFA content of belly fat was greater ($P < 0.01$) than in jowl fat. Concentration of SFA in BF or belly fat of pigs fed LOW was not different, but greater ($P < 0.05$) than that of jowl fat. For pigs fed MED, BF contained similar or greater SFA concentration relative to belly or jowl fat, respectively, and no difference was observed between belly and jowl fat. Pigs fed HIGH had similar concentration of SFA among all 3 fat depots.

There was no dietary treatment × fat depot interaction for MUFA content. Pigs fed CON had a greater ($P < 0.01$) concentration of MUFA than pigs fed diets containing DDGS regardless of fat depot. The MUFA content of pigs fed LOW and MED was not

different, but was greater ($P < 0.01$) than those fed HIGH. Among the 3 fat depots, MUFA concentration of belly and jowl fat was similar, but was higher ($P < 0.01$) than that of BF for all dietary treatments. The results for PUFA content and calculated IV followed the same pattern as that for C18:2, except for pigs fed CON where jowl fat had the greatest ($P < 0.05$) IV relative to other depots, and BF IV was lower ($P < 0.01$) than that of belly fat.

Prediction of ME for DDGS

Gain:feed ratio is a close reflection of dietary energy concentration and therefore, has been used as the primary criterion to access energy estimates of DDGS sources. A detectable difference of 0.01 in overall G:F (SEM = 0.03) was observed in the present study. Predictions from the NRC (2012) growth model suggest that a difference of 80 kcal/kg in dietary ME will alter G:F of pigs by 0.01. Consequently, dietary ME with a variation less than 80 kcal/kg were considered to be similar among the diets fed in this study. This difference in dietary ME is equivalent to a difference of 200 kcal ME/kg in DDGS because the experimental diets contained 40% DDGS. Therefore, the lower limit of sensitivity for detecting differences in ME concentration in this experiment was 200 kcal/kg.

Using equations from Anderson et al. (2012) and GE inputs determined by bomb calorimetry (prediction 2, Table 2.7) resulted in similar ME estimates for LOW, MED, and HIGH DDGS sources, and the predicted values were similar to those provided by ILLUMINATE® (prediction 1). Both prediction 1 and 2 resulted in similar dietary ME content between CON and DDGS treatments. Predicted ME values for DDGS based on the combination of GE = 4583 + (50.61 × EE) - (0.12 × particle size) from Kerr et al.

(2013) and Anderson et al. (2012) equations (prediction 3) were also similar among the 3 sources of DDGS. However, these estimates were approximately 300 kcal/kg less than the predicted ME content of DDGS using prediction 1 and 2, and, consequently, resulted in lower estimated ME content in DDGS diets compared with CON diet. Estimates of ME for DDGS sources from NRC (2012; prediction 4) were similar to those from prediction 1 and 2, and resulted in similar dietary ME among all dietary treatments.

Discussion

Chemical analysis

High-oil DDGS used in this study had an oil concentration of 14.2%, which was representative of the traditional DDGS sources reviewed by Stein and Shurson (2009) before the U.S. ethanol industry implemented oil extraction technologies. In recent years, the majority of ethanol producers in the United States have been extracting oil prior to manufacturing DDGS, which has resulted in a wide range of EE content (5 to 12%; Kerr et al., 2013). The DDGS sources with low- (5.9%) and medium- (9.9%) oil content used in this study represented the low and high ends of this range. Comparing the nutritional composition (Table 2.1) of the DDGS used in the present study, concentration of CP and starch increased as EE content declined. Interestingly, high-oil DDGS contained greater concentrations of NDF, ADF, and TDF than low- and medium-oil DDGS, which indicated that fiber content did not increase as expected when DDGS contained less oil. These observations suggest that with oil extraction, DDGS sources tend to have slightly more CP and starch content, but may not contain higher fiber concentration than traditional high-oil DDGS sources.

Growth performance and carcass composition

Numerous studies have been conducted to evaluate the growth performance of growing-finishing pigs fed diets containing DDGS. In 23 studies reviewed by Stein and Shurson (2009), the majority of studies showed no change in growth performance when up to 30% DDGS was added to growing-finishing pig diets, but 6 studies reported reduced ADFI, and 6 studies showed decreased ADG. Hardman et al. (2013) also reported that overall growth performance was unaffected when 20 and 40% DDGS was included in the diet, but a reduction in ADFI and ADG was observed in pigs fed 60% DDGS compared with those fed corn-soybean meal diets, whereas G:F was not affected. In the present study, greater overall ADFI was observed for pigs fed CON relative to pigs fed diets containing DDGS, which may be a consequence of a greater fiber concentration in the DDGS diets (13.4, 13.7, and 16.3% NDF averaged over 4 phases in LOW, MED, and HIGH diets, respectively; Table 2.2 and 2.3) compared with CON (8.4% NDF averaged over 4 phases). Diets containing 40% DDGS with elevated dietary NDF content likely increase the gut fill of pigs with light BW, which may have caused a lower ADFI and ADG of pigs in phases 2 and 3. However, these pigs were able to maintain similar ADFI and ADG with pigs fed CON in the last phase. This observation is in agreement with previous observations (Xu et al., 2010a; Hardman, 2013) that also showed a reduction of ADFI and ADG in early feeding phases, but not in late phases, when pigs were fed more than 30% DDGS. The ability of pigs to maintain energy intake from fiber-rich diets appears to be related to the physiological age of the animal and the capacity of the gastrointestinal tract to allow consumption of more feed (Kennelly and Aherne, 1980). According to the observed overall G:F, dietary ME content was similar among

CON, MED, and HIGH, but was slightly reduced in LOW. In other words, ME content of the low-oil DDGS source was overestimated in diet formulation. Based on the same overall ADG, ADFI among DDGS treatments, and similar G:F between MED and HIGH, it appears that growth performance of growing-finishing pigs is not affected by variable oil content among sources of DDGS that contain similar predicted ME.

Reduced HCW of pigs fed diets containing DDGS is mainly explained by the reduced ADG and consequently, lower final BW at harvest compared with pigs fed CON. However, reduced LMA was observed for pigs fed DDGS treatments even when final BW was used as a covariate. This observation is likely due to a decreased Lys intake in pigs fed LOW, MED, and HIGH (22.9, 21.7, and 22.4 g/d, respectively) relative to pigs fed CON (25.2 g/d), which may have limited the maximal lean tissue growth in pigs fed DDGS diets. Reduction in carcass yield of pigs fed DDGS diets is consistent with previous studies (Linneen et al., 2008; Xu et al., 2010a; Graham et al., 2014a) that have also reported decreased carcass yield when 30 to 45% DDGS was included in growing-finishing diets. Similar to results reported by Xu et al. (2010a), DDGS used in this study contained more than 3 times the dietary NDF content found in corn and soybean meal. Elevated dietary fiber content negatively affects carcass yield by increasing gut fill and intestine and visceral organ weights (Kass et al., 1980; Pond et al., 1988; Agyekum et al., 2012).

Pork fat quality

The dietary treatment × fat depot interactions observed for SFA, C18:2, PUFA, and IV indicated that the magnitude of change in fatty acid content as the result of feeding different diets (CON vs. DDGS diets), or the different amounts of oil content in

DDGS sources, varied among the three anatomical fat depots. For SFA, differences among fat depots were more prominent in pigs fed CON compared with the DDGS dietary treatments. Pigs fed DDGS diets consumed more dietary lipid (3.43, 4.45, and 6.91% EE averaged over all phases in LOW, MED, and HIGH diets, respectively; Table 2.2 and 2.3) than pigs fed CON (1.97% EE averaged all over phases). Elevated dietary lipid is effective in depressing *de novo* synthesis of fatty acids that are usually more saturated, and favors the deposition of fatty acids directly from dietary lipid (Farnworth and Kramer, 1987; Chilliard, 1993). In this case, corn oil present in DDGS contains a high concentration of PUFA (54% of dietary lipid), but low SFA content (18% of dietary lipid). Therefore, SFA concentration was markedly reduced in pigs fed DDGS treatments, and consequently, differences among fat depots were less prominent compared with pigs fed CON. In contrast, PUFA concentration and IV were greatly increased when 40% DDGS was added to diets, which was commonly observed in previous studies (Benz et al., 2010; Jacela et al., 2010; Graham et al., 2014a). Among the 3 fat depots, jowl fat has the lowest activity of enzymes for lipogenesis, and fat deposition is more dependent on the composition of dietary lipids (Mourot et al., 1995). Therefore, it was expected that jowl fat would be less saturated and contained greater IV relative to BF and belly fat. However, in the current study, the opposite responses were observed in pigs fed diets containing DDGS, because BF had higher concentrations of linoleic acid, PUFA, and IV compared with belly and jowl fat. The reason for this observation is unclear.

Carcass fat IV was decreased when oil concentration of DDGS sources was reduced from 14.2% to 9.9 and 5.9%. This is mainly due to a decrease in dietary C18:2 intake from 96.1 g/d in pigs fed HIGH (averaged over 4 phases) to 48.3 and 62.4 g/d in

pigs fed LOW and MED, respectively. Boyd et al. (1997) suggested that the IV threshold of pork fat should be set at 74 to maintain acceptable pork fat quality. In the present study, belly fat of pigs fed high-oil DDGS had an IV that exceeded the cut-off value, but belly IV of pigs fed low- and medium-oil DDGS was reduced to an acceptable degree. However, based on the comparison of fat depot IV among LOW, MED, and CON, feeding the reduced-oil DDGS sources did not overcome the negative impact of including DDGS in diets on pork fat quality, because pigs fed CON still had the lowest C18:2 intake (29.5 g/d) compared with those fed DDGS treatments.

Prediction of ME for DDGS

Predicted ME of DDGS was provided by ILLUMINATE® at the beginning of the present study. These predictions were used as the basis for selecting the 3 sources of DDGS to achieve our goal of obtaining DDGS sources that contained similar ME, but variable EE content. Except for CON, diets were formulated to contain 40% DDGS with similar amounts of corn and soybean meal within phase so that the ME differences among DDGS diets were only related to ME content of the DDGS sources. As a result, calculated dietary ME content was similar (3,257 to 3,288 kcal/kg; prediction 1) across DDGS treatments within a phase, and we hypothesized that pigs fed the DDGS diets would have similar overall G:F if ME concentrations of DDGS sources were predicted correctly. The observed overall G:F responses indicated that dietary ME was similar in MED, HIGH, and CON. However, the slight reduction in overall G:F for pigs fed LOW indicated that the low-oil DDGS source contained slightly less ME than other DDGS sources. This was not surprising because all published DE and ME prediction equations evaluated by Urriola et al. (2014) represented very few DDGS samples that contained less

than 6% EE. These results validate the accuracy of ME estimates for medium- and high-oil DDGS from ILLUMINATE® and Anderson et al. (2012) equations (prediction 1 and 2, respectively), but also indicate a slight overestimation of ME content for DDGS containing low oil concentration.

Prediction of ME for DDGS requires an input of GE value, and is highly dependent on the accuracy of determining the GE concentration (Urriola et al., 2014). Therefore, GE content measured by bomb calorimetry is preferred when using the Anderson et al. (2012) equations. However, realizing the difficulties of quickly obtaining actual GE values in commercial feed production operations, equations have also been developed to predict GE concentration of feed ingredients (Ewan et al., 1989) and DDGS (Anderson et al., 2012; Kerr et al., 2013) based on chemical composition. Unfortunately, Urriola et al. (2014) reported large discrepancies between actual GE measurements and predicted GE values generated by the published GE equations. If these GE prediction equations are used, the equation from Kerr et al. (2013) had the greatest R^2 and least prediction error. Using the combination of the Kerr et al. (2013) GE prediction equation and the Anderson et al. (2012) ME prediction equations (prediction 3) resulted in about 310 kcal/kg less predicted ME content for all 3 DDGS sources compared with estimates from predictions 1 and 2. The lower estimates of ME in the DDGS sources resulted in about 150 kcal/kg less dietary ME content for LOW, MED, and HIGH diets compared with CON diet. These results suggest that ME content for medium- and high-oil DDGS sources will be underestimated using this approach, and laboratory determined GE should be used as the input for the Anderson et al. (2012) equations.

The NRC (2012) categorized sources of corn DDGS into 3 groups based on oil concentrations: > 10% oil, > 6 and < 9% oil, and < 4 % oil. The medium-oil (9.9%) and high-oil (14.2%) DDGS evaluated in the present study fall into the class of DDGS with > 10% oil; whereas, the low-oil (5.9%) DDGS is close to the category of DDGS with > 6 and < 9% oil. Based on this classification, use of the NRC (2012) estimates for ME of DDGS (prediction 4) correctly predicted the G:F of pigs fed MED and HIGH based on the comparison to those fed CON. However, using ME values from NRC (2012) based on the current classification according to oil concentration also resulted in overestimation of the ME content for DDGS with low oil content.

Current energy prediction equations developed in previous studies were either based on data from DDGS with more than 9% EE (Stein et al., 2006; Pedersen et al., 2007; Stein et al., 2009), or developed for complete diets (Noblet and Perez, 1993). Although Anderson et al. (2012) determined the ME content of corn co-products with EE content ranging from 2.75 to 6.11%, the use of ME estimates from ILLUMINATE® and the robustness of Anderson et al. (2012) ME equations provides acceptable accuracy and precision for estimating ME content of high- and medium-oil DDGS sources, but are not as accurate for estimating ME content of lower oil (< 6%) DDGS sources.

In summary, growing-finishing pigs fed diets containing 40% DDGS are likely to have slightly depressed feed intake and weight gain relative to pigs fed corn-soybean meal diets, which may be explained by the elevated dietary fiber content in DDGS diets. Feeding DDGS with variable oil content, but similar predicted ME content, had no effect on overall growth performance and carcass characteristics of growing-finishing pigs. Reduction in oil content of DDGS decreased PUFA intake of pigs, and thus improved

pork fat quality by reducing IV of carcass fat depots. Furthermore, the ME content of DDGS with medium and high oil content can be accurately and precisely predicted by ILLUMINATE® or using the combination of equations (Anderson et al., 2012): DE = -2,161 + (1.39 × GE) – (20.7 × NDF) – (49.3 × EE) and ME = -261 + (1.05 × DE) – (7.89 × CP) + (2.47 × NDF) – (4.99 × EE) using analyzed GE content from bomb calorimetry. Additional chemical composition and ME determinations are needed to refine equations to accurately predict ME content of low-oil (< 6% EE) DDGS sources for swine.

Table 2.1. Nutrient composition and physical characteristics of feed ingredients (as-fed basis)

Item	Low-oil DDGS[1]	Medium-oil DDGS	High-oil DDGS	Corn	Soybean meal
DM, %	89.60	89.62	90.34	89.44	89.69
CP, %	30.71	29.91	28.57	7.60	46.74
Ether extract, %	5.87	9.85	14.23	4.78	0.98
Ash, %	4.56	4.03	4.62	1.25	6.07
ADF, %	8.12	9.88	15.64	2.23	6.10
NDF, %	28.37	29.80	40.50	9.83	8.44
Total dietary fiber, %	32.31	33.01	44.37	12.12	12.04
Ca, %	0.03	0.02	0.02	0.01	0.45
P, %	0.82	0.80	0.84	0.23	0.61
Starch, %	7.33	4.21	2.68	63.81	1.50
Essential AA, %					
Arg	1.30	1.41	1.36	0.37	3.33
His	0.84	0.82	0.79	0.22	1.24
Ile	1.12	1.14	1.08	0.25	2.10
Leu	3.66	3.62	3.37	0.83	3.57
Lys	1.05	1.08	0.99	0.29	3.02
Met	0.58	0.58	0.60	0.16	0.65
Phe	1.46	1.46	1.36	0.34	2.30
Thr	1.14	1.12	1.08	0.27	1.76
Trp	0.24	0.25	0.21	0.07	0.74
Val	1.53	1.58	1.55	0.37	2.29
Non-essential AA, %					
Ala	2.18	2.12	2.01	0.53	1.97
Asp	1.97	1.93	1.82	0.54	5.27
Cys	0.57	0.52	0.53	0.16	0.66
Glu	4.56	4.07	3.85	1.29	7.80
Gly	1.19	1.16	1.19	0.30	1.91
Hyl	0.11	0.13	0.14	0.02	0.04
Hyp	0.18	0.20	0.23	0.06	0.09
Orn	0.08	0.04	0.04	0.00	0.04
Pro	2.56	2.26	2.14	0.65	2.33
Ser	1.30	1.27	1.20	0.33	1.95
Tau	0.03	0.02	0.02	0.03	0.05
Tyr	1.07	1.08	1.03	0.23	1.60
Particle size, μm	410	350	900	-	-
Bulk density, g/cm^3	0.638	0.631	0.663	-	-
ME[2], kcal/kg	3,258	3,315	3,232	3,395	3,294

[1] Distillers dried grains with solubles (DDGS) containing variable ether extract content but similar predicted ME concentration.

[2] Predicted ME values from a commercial service (ILLUMINATE®; Nutriquest, Mason City, IA) for DDGS sources and recommended ME values from NRC (2012) for corn and soybean meal (dehulled, solvent extracted).

Table 2.2. Diet composition, phase 1 and 2 (as-fed basis)

	Phase 1 (25 to 50 kg BW)				Phase 2 (50 to 75 kg BW)			
Item	CON[1]	LOW[1]	MED[1]	HIGH[1]	CON	LOW	MED	HIGH
Ingredients, %								
Corn	66.62	47.00	48.00	48.00	72.26	50.94	50.96	50.87
Soybean meal	30.49	8.50	8.50	8.50	25.29	6.50	6.50	6.50
DDGS	-	40.00	40.00	40.00	-	40.00	40.00	40.00
Limestone	1.10	2.58	1.43	1.45	0.89	1.39	1.40	1.40
Monocalcium P (21% P)	1.09	0.85	0.90	0.87	0.89	0.21	0.21	0.21
Salt	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
VTM premix[2]	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
L-Lysine HCl	0.02	0.41	0.43	0.45	0.02	0.30	0.29	0.34
DL-Met	0.02	-	-	-	-	-	-	-
L-Thr	-	-	0.02	0.05	-	-	-	-
L-Trp	-	0.01	0.06	0.04	-	0.01	-	0.03
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
ME[3], kcal/kg	3,269	3,234	3,248	3,220	3,287	3,296	3,270	3,243
Analyzed composition								
DM, %	87.10	87.71	88.31	88.35	87.11	87.84	87.85	88.26
CP, %	17.88	20.07	18.76	19.57	18.12	18.70	14.04	18.59
Ether extract, %	1.71	3.29	4.46	6.80	1.93	3.65	4.09	7.39
Crude fiber, %	2.42	3.31	3.65	3.65	2.51	3.55	3.32	4.02
ADF, %	3.75	5.57	6.00	8.55	3.69	5.40	5.82	8.71
NDF, %	6.64	12.51	13.73	15.42	7.52	13.80	13.22	16.58
Ca, %	0.89	1.12	0.75	0.63	0.78	0.63	0.71	0.46
P, %	0.49	0.66	0.63	0.65	0.44	0.49	0.39	0.58
Essential AA, %								
Arg	1.10	0.92	0.95	1.04	1.15	0.87	0.64	0.91
His	0.46	0.49	0.49	0.53	0.47	0.48	0.38	0.49
Ile	0.74	0.74	0.73	0.80	0.78	0.71	0.54	0.71
Leu	1.58	2.04	2.01	2.17	1.63	2.07	1.74	2.04
Lys	0.98	1.06	1.25	1.14	1.03	0.92	0.66	0.91
Met	0.32	0.31	0.30	0.36	0.28	0.33	0.25	0.34
Phe	0.90	0.96	0.94	1.02	0.94	0.94	0.74	0.93
Thr	0.67	0.70	0.74	0.81	0.69	0.72	0.50	0.73
Trp	0.22	0.18	0.22	0.20	0.22	0.17	0.11	0.18
Val	0.81	0.88	0.89	0.96	0.85	0.87	0.68	0.89
Fatty acids, % total lipid								
Linoleic acid	52.40	52.96	52.75	54.82	52.32	52.50	54.66	52.68
SFA[4]	18.76	19.00	18.48	17.13	19.65	18.17	17.40	17.56
MUFA[5]	26.22	26.24	26.50	25.94	25.02	28.15	26.64	28.04
PUFA[6]	55.36	55.29	54.91	56.64	55.57	54.21	56.21	54.31
IV[7]	121.1	120.4	119.8	122.01	120.6	119.6	121.6	119.6

[1] CON = corn-soybean meal control diet; LOW = 40% low-oil distillers dried grains with solubles (DDGS; 5.9% ether extract) diet; MED = 40% medium-oil DDGS (9.9% ether extract) diet; and HIGH = 40% high-oil DDGS (14.2% ether extract) diet.

[2] VTM premix = vitamin-trace mineral premix, which provided the following nutrients per kg of diet: 8,818 IU vitamin A, 1,654 IU vitamin D_3, 33 IU vitamin E, 3.3

mg vitamin K, 5.5 mg riboflavin, 33.1 mg niacin, 22.0 mg pantothenic acid, 0.03 mg vitamin B_{12}, 0.3 mg iodine as ethylenediamine dihydroiodide, 0.3 mg selenium as sodium selenite, 55.1 mg zinc as zinc oxide, 33.1 iron as ferrous sulfate, 5.5 mg manganese as manganous oxide, and 3.9 mg copper as copper sulfate.

[3] Calculated dietary ME based on diet formulation; NRC (2012) recommended ME values were used for corn and soybean meal (dehulled, solvent extracted), and ME estimates from a commercial service (ILLUMINATE®, Nutriquest, Mason City, IA) were used for DDGS sources.

[4] Total saturated fatty acids=([C8:0] + [C10:0] + [C12:0] + [C14:0] + [C16:0] + [C17:0] + [C18:0] + [C20:0] + [C22:0] + [C24:0]); brackets indicate concentration.

[5] Total monounsaturated fatty acids = ([C14:1] + [C16:1] + [C18:1 – 9c] + [C18:1 – 11c] + [C20:1] + [C24:1]); brackets indicate concentration.

[6] Total polyunsaturated fatty acids = ([C18:2*n*-6] + [C18:3*n*-3] + [C18:3*n*-6] + [C20:2] + [C20:4*n*-6]); brackets indicate concentration.

[7] Calculated iodine value = [C16:1] × 0.95 + [C18:1] × 0.86 + [C18:2] × 1.732 + [C18:3] × 2.616 + [C20:1] × 0.785 + [C22:1] × 0.723; brackets indicate concentration (AOCS, 1998).

Table 2.3. Diet composition, phase 3 and 4 (as-fed basis)

	Phase 3 (75 to 100 kg BW)				Phase 4 (100 to 118 kg BW)			
Item	CON[1]	LOW[1]	MED[1]	HIGH[1]	CON	LOW	MED	HIGH
Ingredients, %								
Corn	78.95	55.64	55.66	55.53	82.90	56.36	56.44	56.36
Soybean meal	18.89	2.25	2.24	2.30	15.04	1.67	1.60	1.60
DDGS	-	40.00	40.00	40.00	-	40.00	40.00	40.00
Limestone	0.78	1.21	1.22	1.22	0.76	1.17	1.18	1.18
Monocalcium P (21% P)	0.70	-	-	-	0.61	-	-	-
Salt	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
VTM premix[2]	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
L-Lysine HCl	0.03	0.25	0.23	0.28	0.04	0.15	0.13	0.19
L-Trp	-	-	-	0.02	-	-	-	0.02
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
ME[3], kcal/kg	3,305	3,314	3,288	3,261	3,312	3,314	3,288	3,261
Analyzed composition								
DM, %	87.04	87.07	88.23	87.72	86.49	87.34	87.92	88.06
CP, %	19.50	17.23	16.89	16.02	13.69	15.59	15.61	15.91
Ether extract, %	2.10	3.51	4.74	7.02	2.12	3.28	4.49	6.44
Crude fiber, %	3.90	3.40	3.66	3.68	1.90	3.14	3.17	3.95
ADF, %	7.25	5.06	6.07	9.07	3.26	4.36	5.85	8.62
NDF, %	12.90	14.16	14.28	17.07	6.67	13.30	13.70	15.95
Ca, %	0.64	0.57	0.56	0.39	0.56	0.67	0.42	0.45
P, %	0.45	0.47	0.45	0.46	0.42	0.41	0.42	0.47
Essential AA, %								
Arg	0.93	0.77	0.76	0.74	0.79	0.68	0.74	0.75
His	0.49	0.45	0.44	0.43	0.35	0.42	0.43	0.41
Ile	0.74	0.65	0.63	0.60	0.55	0.59	0.61	0.58
Leu	2.03	1.99	1.92	1.88	1.32	1.82	1.90	1.75
Lys	0.98	0.77	0.76	0.69	0.71	0.71	0.66	0.70
Met	0.32	0.31	0.28	0.31	0.21	0.27	0.29	0.29
Phe	0.96	0.87	0.84	0.81	0.70	0.79	0.83	0.78
Thr	0.74	0.67	0.58	0.63	0.48	0.61	0.63	0.55
Trp	0.15	0.15	0.13	0.14	0.16	0.13	0.14	0.14
Val	0.90	0.81	0.78	0.78	0.63	0.74	0.76	0.74
Fatty acids, % total lipid								
Linoleic acid	53.45	52.95	53.79	53.16	57.97	52.26	52.49	53.23
SFA[4]	18.77	17.56	17.37	17.70	15.16	18.04	19.27	17.39
MUFA[5]	25.49	27.73	27.18	26.89	24.96	27.77	26.56	27.55
PUFA[6]	55.50	54.56	55.44	55.04	59.37	53.83	54.60	54.76
IV[7]	119.9	119.8	120.8	120.1	125.5	118.5	119.3	119.9

[1] CON = corn-soybean meal control diet; LOW = 40% low-oil distillers dried grains with solubles (DDGS; 5.9% ether extract) diet; MED = 40% medium-oil DDGS (9.9% ether extract) diet; and HIGH = 40% high-oil DDGS (14.2% ether extract) diet.

[2] VTM premix = vitamin-trace mineral premix, which provided the following nutrients per kg of diet: 8,818 IU vitamin A, 1,654 IU vitamin D_3, 33 IU vitamin E, 3.3 mg vitamin K, 5.5 mg riboflavin, 33.1 mg niacin, 22.0 mg pantothenic acid, 0.03 mg vitamin B_{12}, 0.3 mg iodine as ethylenediamine dihydroiodide, 0.3 mg selenium as sodium selenite, 55.1 mg zinc as zinc oxide, 33.1 iron as ferrous sulfate, 5.5 mg manganese as manganous oxide, and 3.9 mg copper as copper

sulfate.

[3] Calculated dietary ME based on diet formulation; NRC (2012) recommended ME values were used for corn and soybean meal (dehulled, solvent extracted), and ME estimates from a commercial service (ILLUMINATE®, Nutriquest, Mason City, IA) were used for DDGS sources.

[4] Total saturated fatty acids=([C8:0] + [C10:0] + [C12:0] + [C14:0] + [C16:0] + [C17:0] + [C18:0] + [C20:0] + [C22:0] + [C24:0]); brackets indicate concentration.

[5] Total monounsaturated fatty acids = ([C14:1] + [C16:1] + [C18:1 – 9c] + [C18:1 – 11c] + [C20:1] + [C24:1]); brackets indicate concentration.

[6] Total polyunsaturated fatty acids = ([C18:2*n*-6] + [C18:3*n*-3] + [C18:3*n*-6] + [C20:2] + [C20:4*n*-6]); brackets indicate concentration.

[7] Calculated iodine value = [C16:1] × 0.95 + [C18:1] × 0.86 + [C18:2] × 1.732 + [C18:3] × 2.616 + [C20:1] × 0.785 + [C22:1] × 0.723; brackets indicate concentration (AOCS, 1998).

Table 2.4. Effects of dietary distillers dried grains with solubles (DDGS) with variable ether extract (EE) content on growth performance of growing-finishing pigs

		40% DDGS			
Item	CON[1]	LOW[1]	MED[1]	HIGH[1]	SEM
No. Pens	12	12	12	12	
BW, kg					
Initial[2]	39.24	39.52	38.95	39.58	0.90
Final	122.66[a]	118.65[b]	118.59[b]	119.44[b]	0.90
ADFI, kg					
Phase 1	2.06	2.01	1.95	1.98	0.04
Phase 2	2.55[a]	2.48[ab]	2.40[b]	2.43[b]	0.04
Phase 3	3.05[a]	2.93[b]	2.88[b]	2.86[b]	0.04
Phase 4	3.23	3.20	3.21	3.12	0.04
Overall	2.72[a]	2.65[ab]	2.61[b]	2.60[b]	0.03
P-value					
Diet			0.017		
Phase			< 0.01		
Diet × phase			0.622		
ADG, kg					
Phase 1	0.97[a]	0.87[b]	0.87[b]	0.89[b]	0.02
Phase 2	0.98[a]	0.94[ab]	0.93[b]	0.93[b]	0.02
Phase 3	0.99[a]	0.95[b]	0.95[ab]	0.93[b]	0.02
Phase 4	0.93	0.91	0.95	0.95	0.02
Overall	0.97[a]	0.92[b]	0.92[b]	0.93[b]	0.01
P-value					
Diet			< 0.01		
Phase			< 0.01		
Diet × phase			0.062		
G:F					
Phase 1	0.471[a]	0.436[b]	0.449[b]	0.451[b]	0.006
Phase 2	0.386	0.382	0.386	0.386	0.006
Phase 3	0.326	0.324	0.331	0.326	0.006
Phase 4	0.289[ab]	0.284[a]	0.295[ab]	0.303[b]	0.006
Overall	0.368[a]	0.356[b]	0.365[a]	0.367[a]	0.003
P-value					
Diet			0.025		
Phase			< 0.01		
Diet × phase			0.061		

[1] CON = corn-soybean meal control diet; LOW = low-oil DDGS (5.9% EE) diet; MED = medium-oil DDGS (9.9% EE) diet; and HIGH = high-oil DDGS (14.2% EE) diet.

[2] Body weight of pigs when feeding experimental diets started.

[ab] Means with different superscripts within a row differ ($P < 0.05$).

Table 2.5. Effects of dietary distillers dried grains with solubles (DDGS) with variable ether extract (EE) content on carcass characteristics

		40% DDGS				
Item	CON[1]	LOW[1]	MED[1]	HIGH[1]	SEM	*P*-value
HCW, kg	90.97[a]	86.69[b]	86.80[b]	87.24[b]	0.88	<0.01
Carcass yield, %	74.2[a]	73.0[b]	72.9[b]	73.0[b]	0.2	<0.01
Backfat depth[2], mm	20.6	19.9	19.2	19.8	0.5	0.288
LM area[2], cm^2	42.06[a]	39.38[b]	39.09[b]	39.37[b]	0.53	<0.01
Fat-free lean[2], %	51.9	51.6	51.9	51.6	0.3	0.858

[1] CON = corn-soybean meal control diet; LOW = low-oil DDGS (5.9% EE) diet; MED = medium-oil DDGS (9.9% EE) diet; and HIGH = high-oil DDGS (14.2% EE) diet.

[2] Final BW was used as covariate in the statistical analysis.

[ab] Means with different superscripts within a row differ ($P < 0.05$).

Table 2.6. Effects of dietary distillers dried grains with solubles (DDGS) and fat depots on the fatty acid profile of carcass fat samples

	CON[1]			LOW[1]			MED[1]			HIGH[1]			Pooled	*P*-values		
Item[2]	Back	Belly	Jowl	Back	Belly	Jowl	Back	Belly	Jowl	Back	Belly	Jowl	SEM	Diet	Depot	Diet× depot
C14:0	1.41^{d}	1.57^{e}	1.39^{d}	1.19^{ab}	1.42^{d}	1.27^{bc}	1.19^{ab}	1.42^{d}	1.27^{bc}	1.11^{a}	1.33^{cd}	1.18^{b}	0.03	<0.01	<0.01	0.29
C16:0	25.66^{h}	24.99^{g}	23.51^{f}	21.84^{cd}	22.65^{e}	21.67^{cd}	21.64^{cd}	22.16^{de}	21.40^{bc}	20.67^{ab}	21.18^{bc}	20.46^{a}	0.28	<0.01	<0.01	<0.01
C16:1	2.32^{cd}	3.35^{f}	2.97^{e}	1.66^{ab}	2.61^{cd}	2.50^{cd}	1.70^{ab}	2.61^{d}	2.37^{cd}	1.43^{a}	2.30^{c}	1.95^{b}	0.11	<0.01	<0.01	0.50
C18:0	13.57^{f}	10.60^{e}	10.12^{de}	10.31^{de}	9.15^{bc}	8.91^{abc}	10.30^{de}	8.80^{ab}	8.84^{ab}	9.72^{cd}	8.26^{a}	8.75^{ab}	0.30	<0.01	<0.01	<0.01
C18:1	39.05^{fg}	41.26^{h}	42.14^{h}	35.35^{b}	38.09^{ef}	39.17^{g}	35.78^{bc}	38.19^{efg}	38.72^{fg}	34.08^{a}	37.00^{de}	36.82^{cd}	0.43	<0.01	<0.01	0.53
C18:2	10.28^{ab}	9.50^{a}	10.97^{b}	22.02^{d}	17.86^{c}	17.72^{c}	21.76^{d}	18.50^{c}	18.70^{c}	25.62^{e}	21.87^{d}	22.48^{d}	0.56	<0.01	<0.01	<0.01
C18:3	0.42^{a}	0.46^{ab}	0.40^{a}	0.63^{cd}	0.56^{bc}	0.48^{ab}	0.62^{cd}	0.57^{bcd}	0.46^{ab}	0.68^{d}	0.64^{cd}	0.64^{cd}	0.04	<0.01	<0.01	0.44
C20:0	0.28^{e}	0.23^{ab}	0.22^{ab}	0.26^{de}	0.23^{abc}	0.22^{ab}	0.25^{d}	0.23^{b}	0.22^{a}	0.25^{cd}	0.23^{ab}	0.23^{ab}	0.01	0.84	<0.01	0.06
C20:1	0.79^{c}	0.74^{bc}	0.48^{a}	0.66^{b}	0.70^{bc}	0.70^{bc}	0.69^{bc}	0.71^{bc}	0.66^{b}	0.66^{b}	0.69^{bc}	0.74^{bc}	0.04	0.94	0.04	<0.01
C20:2	0.49^{a}	0.50^{a}	0.47^{a}	0.94^{cd}	0.83^{b}	0.95^{cd}	0.96^{d}	0.87^{bc}	0.98^{de}	1.07^{e}	0.97^{d}	1.14^{f}	0.03	<0.01	<0.01	<0.01
SFA[3]	41.69^{h}	38.17^{g}	36.02^{f}	34.43^{e}	34.23^{e}	32.82^{bcd}	34.20^{de}	33.42^{cde}	32.49^{abc}	32.52^{abc}	31.75^{ab}	31.33^{a}	0.52	<0.01	<0.01	<0.01
MUFA[4]	45.33^{d}	49.59^{e}	49.75^{e}	40.12^{b}	44.77^{d}	45.87^{d}	40.66^{b}	44.86^{d}	45.12^{d}	38.30^{a}	43.03^{c}	42.43^{c}	0.58	<0.01	<0.01	0.58
PUFA[5]	11.51^{ab}	10.79^{a}	12.23^{b}	24.05^{d}	19.68^{c}	19.63^{c}	23.78^{d}	20.38^{c}	20.58^{c}	27.81^{e}	23.92^{d}	24.75^{d}	0.60	<0.01	<0.01	<0.01
IV[6]	57.72 ^{a}	60.17^{b}	62.20^{c}	74.11^{ef}	70.74^{d}	71.22^{d}	74.35^{fg}	72.03^{de}	72.25^{de}	78.96^{i}	76.41^{gh}	76.89^{h}	0.79	<0.01	<0.01	<0.01

[1] CON = corn-soybean meal control diet; LOW = 40% low-oil DDGS (5.9% ether extract) diet; MED = 40% medium-oil DDGS (9.9% ether extract) diet; and HIGH = 40% high-oil DDGS (14.2% ether extract) diet.

[2] Concentrations of fatty acids are expressed as grams of fatty acid/100g fat. Fatty acids: myristic (C14:0), palmitic (C16:0), palmitoleic (C16:1), stearic (C18:0), oleic (C18:1), linoleic (C18:2), linolenic (C18:3), arachidic (C20:0), gadoleic (C20:1), eicosadienoic (C20:2).

[3] Total saturated fatty acids=([C8:0] + [C10:0] + [C12:0] + [C14:0] + [C16:0] + [C17:0] + [C18:0] +[C20:0] + [C22:0] + [C24:0]); brackets indicate concentration.

[4] Total monounsaturated fatty acids = ([C14:1] + [C16:1] + [C18:1 – 9c] + [C18:1 – 11c] + [C20:1] + [C24:1]); brackets indicate concentration.

[5] Total polyunsaturated fatty acids = ([C18:2*n*-6] + [C18:3*n*-3] + [C18:3*n*-6] + [C20:2] + [C20:4*n*-6]); brackets indicate concentration.

[6] Calculated iodine value = [C16:1] × 0.95 + [C18:1] × 0.86 + [C18:2] × 1.732 + [C18:3] × 2.616 + [C20:1] × 0.785 + [C22:1] × 0.723; brackets indicate concentration (AOCS, 1998).

[a-h] Means with different superscripts within a row differ ($P < 0.05$).

Table 2.7. Prediction of energy (kcal/kg as-fed) content for sources of distillers grains with solubles (DDGS) and diets

Item	Source of estimates	LOW	MED	HIGH	CON
Prediction 1					
DDGS ME	ILLUMINATE®[1]	3,258	3,315	3,232	-
Weighted dietary ME[2]	-	3,261	3,288	3,257	3,296
Prediction 2					
DDGS GE	Bomb calorimetry	4,607	4,703	4,940	-
DDGS ME	Anderson et al. (2012)[3]	3,349	3,286	3,215	-
Weighted dietary ME[2]	-	3,297	3,277	3,250	3,296
Prediction 3					
DDGS GE	Kerr et al. (2013)[4]	4,359	4,568	4,763	-
DDGS ME	Anderson et al. (2012)	2,974	3,031	2,853	-
Weighted dietary ME[2]	-	3,147	3,174	3,105	3,296
Prediction 4					
DDGS ME	NRC (2012)[5]	3,396	3,434	3,434	-
Weighted dietary ME[2]	-	3,316	3,336	3,337	3,296

[1] A commercial service provided by Nutriquest (Mason City, IA) that uses chemical composition of DDGS and prediction equations to estimate energy values of the majority of DDGS sources produced by U.S. ethanol plants.

[2] Calculated ME content of diets based on diet formulation; values are presented as the average over 4 phases and weighted for feed disappearance in each phase; NRC (2012) recommended ME values were used for corn and soybean meal (dehulled, solvent extracted).

[3] Refers to DE = -2,161 + (1.39 × GE) – (20.7 × NDF) – (49.3 × EE) and ME = -261 + (1.05 × DE) – (7.89 × CP) + (2.47 × NDF) – (4.99 × EE).

[4] Refers to GE = 4,583 + (50.61 × EE) - (0.12 × particle size).

[5] Recommended ME of corn DDGS (> 10% oil) for MED and HIGH, and recommended ME of corn DDGS (> 6 and < 9% oil) for LOW.

CHAPTER 3

Evaluation of NE predictions and the impact of feeding distillers dried grains with solubles (DDGS) with variable NE content on growth performance and carcass characteristics of growing-finishing pigs

Summary

Growing-finishing pigs (n = 432; initial BW: 22.0 ± 4.3 kg) were utilized to measure growth performance and carcass characteristics when fed 4 sources of DDGS with a wide range in predicted NE content. Pigs were blocked by initial BW, and within blocks, pens were randomly allotted to 1 of 4 dietary treatments (9 pigs/pen, 12 replicates/treatment). Dietary treatments consisted of 4 corn and soybean meal based diets containing 40% DDGS from different sources with increasing NE (as-fed) content predicted by a commercial service: 1) source A with low NE (2,083 kcal/kg; LOW), 2) source B with medium-low NE (2,255 kcal/kg; ML), 3) source C with medium-high NE (2,469 kcal/kg; MH), and 4) source D with high NE (2,743 kcal/kg; HIGH). The content of NE in DDGS was predicted by an equation-based system. Diets met or exceeded nutrient requirements and were calculated to contain the same standardized ileal digestible Lys:NE within phases. Overall, ADFI of pigs fed ML was greater ($P < 0.05$) than pigs fed MH and HIGH, but not different from LOW, and no differences were observed among LOW, MH, and HIGH. Pigs fed ML had similar ADG with LOW and HIGH, but less ($P < 0.05$) than that of pigs fed MH, and no differences were observed among LOW, MH, and HIGH. Gain:feed was reduced ($P < 0.02$) in pigs fed ML compared with other dietary treatments. No treatment differences ($P > 0.19$) were observed in HCW, carcass yield, backfat depth, LM area, and percentage of carcass fat-free lean. The NRC (2012) model was used to estimate NE content of diets by matching

the model-predicted G:F with the observed G:F. Using NE content values for corn and soybean meal based on NRC (2012), NE content was calculated for DDGS sources A, B, C, and D (2,377, 1,924, 2,612, and 2,513 kcal/kg, respectively). Predicted NE values from 8 identified equations were calculated and compared with model-determined NE of DDGS. Results indicated that G:F responses of pigs did not correspond to increasing NE estimates of the 4 DDGS sources provided by the commercial service, and suggest that NE content might have been overestimated for sources B and D, and underestimated for the sources A and C. Feeding 40% DDGS with less NE content increased ADFI and reduced ADG and G:F, but carcass traits were not affected when the difference of NE content is less than 700 kcal/kg among DDGS sources. In addition, current NE prediction systems need to be revised for better prediction of NE content among sources of DDGS.
Key words: DDGS, growing-finishing pigs, NE, prediction equations

Introduction

Corn distillers dried grains with solubles (**DDGS**) is a co-product of ethanol production that has been used widely in swine diets as a cost effective source of energy and AA. Variability in the chemical composition and nutrient digestibility has been reported among DDGS sources (Stein and Shurson, 2009; Anderson et al., 2012). Implementation of oil extraction procedures by most ethanol plants has further increased the variability in energy values among sources of DDGS (Kerr et al., 2013). However, limited data are available to show the impact of feeding DDGS with variable NE content on the growth and carcass responses of growing-finishing pigs.

The NE system represents the energy requirements of pigs fed high-fiber diets better than the ME system (Noblet et al., 1994b). As a result, the NE system is being

adopted increasingly in the U.S. to facilitate more efficient use of economical high-fiber ingredients like DDGS in commercial swine diet formulations. Traditionally, NE of feedstuffs has been determined using comparative slaughter or indirect calorimetry, which are labor intensive and require expensive equipment. Therefore, a relatively low cost, fast, and accurate method is needed to determine the NE content of DDGS sources. Empirical NE equations (Noblet et al., 1994b), based on analyzed chemical composition, have been developed for use in complete feed, but have not been validated for use with individual ingredients. More recently, a NE prediction equation (Graham et al., 2014b) and commercial service (ILLUMINATE®; Nutriquest, Mason City, IA) have been developed for rapid and low cost estimation of NE content of DDGS sources, but accuracy of these methods has not been evaluated. Therefore, the objectives of this experiment were to determine the growth performance and carcass traits of growing-finishing pigs fed 4 DDGS sources with variable NE content, and to evaluate the utility of published NE equations and ILLUMINATE® to predict NE values for the DDGS sources used.

Materials and methods

All experimental procedures in this study were approved by the University of Minnesota Institutional Animal Care and Use Committee (St. Paul, MN).

Animals and housing

Barrows (n = 432) were blocked by initial BW (22.0 ± 4.3 kg) and allotted to 12 blocks (4 pens/block; 9 pigs/pen). Pigs were housed in an environmentally-controlled grow-finish facility at the University of Minnesota West Central Research and Outreach Center (Morris, MN). Each pen (1.60 × 4.5 m) consisted of completely slatted, concrete

floors, and was equipped with a nipple waterer and 1 single-sided self-feeder with 4 feeding spaces. Room temperature of the facility was maintained at about 20°C. Pigs were allowed ad libitum access to feed and water throughout the experiment. Pigs that showed signs of poor health were treated individually with appropriate medication or removed from the experiment.

Diets and experimental design

ILLUMINATE® is a proprietary commercial service that uses chemical composition of DDGS sources and published equations to estimate DE, ME, NE, and standardized ileal digestible (**SID**) AA content of the majority of DDGS sources produced by ethanol plants in the U.S. Energy estimates for DDGS sources provided by ILLUMINATE® were used as the basis for selecting 4 sources of DDGS with increasing concentrations of predicted NE (as-fed) for this study. The 4 sources contained: 1) 2,083 kcal NE/kg for DDGS source A, 2) 2,255 kcal NE/kg for DDGS source B, 3) 2,469 kcal NE/kg for DDGS source C, and 4) 2,743 kcal NE/kg for DDGS source D. Each source of DDGS and 1 source of corn were obtained in single lots, and samples were collected for chemical analyses that were used in diet formulation (Table 3.1). Soybean meal was obtained in multiple lots from the same supplier, and analyzed nutrient composition of a sample obtained from the first lot was used to formulate diets throughout the experiment.

Pens of pigs were allotted randomly to 1 of 4 dietary treatments (Table 3.2 and 3.3) in a 4-phase feeding program (22 to 50 kg, 50 to 75 kg, 75 to 100 kg, and 100 to 115 kg BW). Phases were switched when average BW of pigs in the pen reached the targeted starting BW ± 2.3 kg of the subsequent phase. Dietary treatments consisted of corn-soybean meal based diets with: 1) 40% DDGS A with low predicted NE (**LOW**), 2) 40%

DDGS B with medium-low predicted NE (**ML**), 3) 40% DDGS C with medium-high predicted NE (**MH**), and 4) 40% DDGS D with high predicted NE (**HIGH**). Diets were balanced for SID AA and standardized total tract digestible (**STTD**) P, and were calculated to contain the same SID Lys:NE within phases. The coefficients of AA digestibility for DDGS sources were obtained from equations reported by Almeida et al. (2013) based on analyzed AA composition. Energy values and coefficients for SID AA and STTD P of corn and soybean meal and the coefficient for STTD P of DDGS used in diet formulation were obtained from NRC (2012). All diets met or exceeded the nutrient requirements of growing-finishing pigs, which were estimated using the NRC (2012) model. Model inputs were based on growth performance and lean growth rate of pigs fed a corn-soybean meal diet in a similar experiment (chapter 2) conducted in the same facilities with the same genetic line of pigs. Body weight of individual pigs and feed disappearance in each pen were measured every 2 weeks (period) to calculate ADG, ADFI, and G:F. Pigs were fed a common corn-soybean meal diet for 5 d prior to harvest (holding diet; Table 3.3) in the both harvest groups. Switching to corn-soybean meal diets for the short duration before harvest was done because actual ADFI was greater than predicted ADFI and the supply of each source of DDGS was depleted before the trial concluded. Feed samples were obtained and frozen (-20°C) when each batch of feed was mixed, and 4 samples of each dietary treatment (1 sample from each of the 4 phases) and 1 sample of the holding diet were selected randomly for analysis of nutrient composition.

Carcass measurements

When the average BW of pigs reached 75 kg and 110 kg, backfat (**BF**) depth and loin muscle area (**LMA**) were measure between the 10th and 11th ribs using an ALOKA

500V real-time ultrasound machine (Corometrics Medical Systems, Wallingford, CT) by a certified technician. Pigs were divided into 2 groups (pigs from blocks 1 to 6 with the greatest initial BW were in group 1, and pigs from blocks 7 to 12 with the lowest initial BW were in group 2) and harvested at 2 times that were 11 d apart. For each harvest group, after ultrasound measurements were obtained, final BW was determined and pigs were tattooed individually and transported to a commercial abattoir (Hormel Foods; Austin, MN). Hot carcass weight was recorded at harvest and was used to calculate carcass yield using: carcass yield, % = HCW/final BW × 100. Carcasses of 14 pigs were trimmed during USDA inspection, so their HCW data were removed from the data set used in the analysis. Percentage of carcass fat free lean (**FFL%**) was calculated using: FFL% = {[2.620 + (0.456 × sex of pig) – (3.358 × 10th rib BF depth, cm) + (0.306 × 10th rib LMA, cm^2) + (0.401 × HCW, kg)]/HCW, kg} × 100, where sex of pig is defined as barrow = 1 and gilt = 2 (NPPC, 2000).

Chemical analysis

Six feed ingredient samples (4 sources of DDGS, 1 source of corn, 1 source of soybean meal) and 17 complete diets were analyzed for nutrient composition at University of Missouri Agricultural Experiment Station Chemical Laboratory (Columbia, MO). Standard procedures of AOAC (2006) were followed for analysis of moisture (Method 934.01), CP (Method 990.03), ether extract (**EE**; Method 920.39), crude fiber (Method 978.10), ADF (Method 973.18), NDF (Holst, 1973), Ca and P (Method 985.01), AA profile (Method 982.30), and starch content (AACC, Approved Methods, No. 76-13).

Energy determination of DDGS

Gross energy of DDGS was determined using bomb calorimetry (Model 1281,

Parr Instrument Co., Moline, IL). Digestible energy and ME of each DDGS source were obtained using equations: DE = -2,161 + (1.39 × GE) – (20.7 × NDF) – (49.3 × EE) and ME = -261 + (1.05 × DE) –(7.89 × CP) + (2.47 × NDF) – (4.99 × EE) from Anderson et al. (2012), which were evaluated and validated by Urriola et al. (2014) and Wu (chapter 2).

Estimates of NE concentration for each DDGS source were calculated using overall G:F responses observed and the NRC (2012) growth model as follows:

Step 1. Standard growth potential (growth curve) of pigs used in the present experiment was defined using the "User observed intake as model input" option, which was based on observed overall ADFI (2.721 kg/d) and initial and final BW (39.2 and 122.7 kg, respectively) of 12 pens of pigs (n = 108) fed corn-soybean meal control diets in a previous experiment (chapter 2). This previous experiment was conducted in the same facility with the same genetics, gender, and a similar feeding program and similar environment conditions to the present study. Dietary NE of the control diet from the previous experiment was calculated based on diet formulation and NE values of corn (2,672 kcal/kg) and soybean meal (2,087 kcal/kg) from NRC (2012).

Step 2. The whole body protein deposition (**Pd**) was defined using the "Specify mean Pd and gender" option, which was based on observed carcass composition of pigs fed the corn-soybean meal control diets in the previous experiment, conducted in the same facilities and under similar conditions. Mean Pd rate was calculated using the following equations suggested by NPPC (2000):

Initial FFL, kg = (0.418 × initial BW, kg) – 1.656

Final FFL, kg = 2.620 + (0.456 × sex of pig) – (3.358 × 10th rib BF depth, cm) +

(0.306 × 10th rib LMA, cm^2) + (0.401 × HCW, kg), where sex of pig is defined as barrow = 1 and gilt = 2

Lean gain, kg/d = (final FFL, kg – initial FFL, kg)/days from initial to final

Pd, g/day = (lean gain, g/day)/2.55

Step 3: For each feeding period (2 wk; 6 periods total) in the present experiment, NE content of a dietary treatment was obtained by adjusting dietary NE inputs until G:F predicted by the model matched the observed G:F. Analyzed least-squares means of BW and G:F of pigs fed each dietary treatment were used in this calculation.

Step 4: Based on the assumption that corn, soybean meal, and DDGS were the only energy-containing ingredients in the diets, NE content of DDGS was determined by subtracting NE of corn and soybean meal derived from NRC (2012) from the dietary NE and adjusting for the percentage (40%) of DDGS in the diet. Finally, the mean NE content of DDGS was determined by calculating the average among the 6 periods weighted for total feed consumption in each period.

Evaluation of NE predictions

Predicted NE of each DDGS source was calculated using equations 4, 5, 7, 8, 9, 10, and 11 from Noblet et al. (1994b; energy expressed as kcal/kg and composition expressed as g/kg DM):

Eq. 4: NE = (0.703 × DE) + (1.58 × EE) + (0.47 × starch) – (0.97 × CP) – (0.98 × crude fiber)

Eq. 5: NE = (0.700 × DE) + (1.61 × EE + (0.48 × starch) – (0.91 × CP) – (0.87 × ADF)

Eq. 7: NE = (0.730 × ME) + (1.31 × EE) + (0.37 × starch) – (0.67 × CP) – (0.97 ×

crude fiber)

Eq. 8: NE = (0.726 × ME) + (1.33 × EE) + (0.39 × starch) – (0.62 × CP) – (0.83 × ADF)

Eq. 9: NE = 2,796 + (4.15 × EE) + (0.81 × starch) – (7.07 × ash) – (5.38 × crude fiber)

Eq. 10: NE = 2,790 + (4.12 × EE) + (0.81 × starch) – (6.65 × ash) – (4.72 × ADF)

Eq. 11: NE = 2,875 + (4.38 × EE) + (0.67 × starch) – (5.50 × ash) – [2.01 × (NDF – ADF)] – (4.02 × ADF),

and also the equation from Graham et al. (2014b; energy expressed as kcal/kg and composition expressed as % DM):

NE = (115.011 × EE) + 1,501.01

Net energy estimates from prediction equations and ILLUMINATE® were compared with the estimated NE content of DDGS determined using steps 1 to 4 described above. Prediction error (**PE**) and bias were calculated using the following equations adapted from Urriola et al. (2014):

$$PE = \sqrt[2]{\frac{1}{n}\sum_{i=1}^{n}(yi - \hat{y}i)^2}$$

and

$$Bias = \frac{1}{n}\sum_{i=1}^{n}(yi - \hat{y}i)$$

, where y_i is the predicted value for the ith observation, $\hat{y}_i$ is the determined (model-calculated) value for the ith observation, and n is the total number of observations (Lane et al., 2014). We assumed the NE estimates derived from the current experiment using

steps 1 to 4 were the most accurate estimates of actual NE content of the DDGS sources and therefore, served as the basis for the comparison.

Statistical analysis

All analyses were conducted using the MIXED procedure (SAS Inst. Inc., Cary, NC) in a randomized complete block design. Pen served as the experimental unit for all data analyses. Growth performance data of each period were analyzed, and overall ADFI, ADG, and G:F were generated using a statistical model that included dietary treatment as a fixed effect and block as a random effect with repeated measures in time. For analysis of carcass characteristics, dietary treatment was a fixed effect and block was a random effect. Body weight was measured during the same week when ultrasound measurement was performed, and was used as a covariate to adjust BF depth, LMA, and FFL% if the covariate effect was significant ($P < 0.05$). Means were reported as least-squares means and were separated by the PDIFF option when $P < 0.05$, and trends are reported when $0.05 < P < 0.10$.

Results

Growth performance and carcass composition

Six pigs (1, 3, and 2 pigs from LOW, ML, and MH treatments, respectively) were removed from the study because of death or poor health. A significant interaction ($P < 0.01$) of dietary treatment × period was observed for BW (Table 3.4). However, no treatment differences were detected for BW in any period or for final BW. There was a dietary treatment × period interaction ($P < 0.01$) for ADFI. In periods 1 to 3, pigs had similar ADFI regardless of dietary treatment. In period 4, however, ADFI of pigs fed ML was greater ($P < 0.05$) than that of pigs fed MH and HIGH, but not different from LOW,

and ADFI of pigs fed LOW was similar to that of pigs fed MH but greater ($P < 0.05$) than pigs fed HIGH. Pigs fed ML had a greater ($P < 0.05$) ADFI compared with other dietary treatments in period 5 and 6, and no differences were observed among pigs fed LOW, MH, and HIGH diets. Overall, ADFI of pigs fed ML was greater ($P < 0.05$) than that of pigs fed MH and HIGH, but was not different from pigs fed LOW. No differences in overall ADFI were observed among LOW, MH, and HIGH treatments. A tendency ($P = 0.075$) for a dietary treatment × period interaction was observed for ADG. In period 1, ADG of pigs fed ML was lower ($P < 0.05$) than that of pigs fed MH, but was not different from LOW and HIGH, and no differences were observed among LOW, MH, and HIGH. Pigs fed LOW had a greater ($P < 0.05$) ADG than those fed ML and HIGH, but were not different from MH in period 2, and no differences were found among pigs fed ML, MH, and HIGH. In period 3, ADG of pigs fed LOW was similar compared with pigs fed MH and HIGH, but was greater ($P < 0.05$) than ML, and no differences were observed among ML, MH, and HIGH. In period 4, the results followed the same pattern as that for period 2. No treatment differences in ADG were observed in period 5. In period 6, ADG of pigs fed MH was greater ($P < 0.05$) than LOW and HIGH but not different from ML, and ADG of pigs fed ML was similar with those fed MH and HIGH but greater ($P < 0.05$) than LOW. No difference was observed between pigs fed LOW and HIGH in period 6. Overall, ADG of pigs fed ML was less ($P < 0.05$) than for pigs fed MH and tended ($P = 0.087$) to be less than that of pigs fed LOW, but was not different from pigs fed HIGH. No differences in ADG were observed among pigs fed LOW, MH, and HIGH over the entire growing-finishing period. No dietary treatment ×

period interaction ($P = 0.484$) was observed for G:F. The overall G:F of pigs fed LOW, MH, and HIGH were not different, but were higher ($P < 0.05$) than that of pigs fed ML.

Hot carcass weight, carcass yield, and FFL% were not different among all dietary treatments (Table 3.5). No treatment differences were observed for BF depth or LMA at either the end of growing phase (average BW of 75 kg) or the end of finishing phase (average BW of 110 kg). Pigs had a similar amount of increased BF depth and LMA between the two ultrasonic measurements.

Model calculation and equation evaluation

Based on the NRC (2012) model calculations using observed G:F responses in this experiment, NE concentration was lower in DDGS B compared with other DDGS sources (Table 3.6). In contrast, DDGS C contained the greatest NE value among the sources, which was 688 kcal/kg higher than the DDGS B; sources D and A had the 2nd and 3rd highest NE values, which were 589 and 453 kcal/kg, respectively, greater than that of the DDGS B.

Prediction of NE content from ILLUMINATE® resulted in the least bias and a moderate PE (> 200 and < 300 kcal/kg). Among the Noblet et al. (1994b) equations, estimates from equation 9 had the least PE with a moderate bias (> 100 and < 200 kcal/kg); using equation 4, 5, 7, and 8 resulted in relatively low PE and biases compared with estimates using equation 10 and 11. The Graham et al. (2014b) equation generated NE estimates that had the greatest PE and biases compared with other predictions.

Discussion

Growth performance and carcass characteristics

Several studies have been conducted to investigate growth responses of pigs fed diets containing variable energy concentrations. Beaulieu el al. (2009) observed a linear decrease in ADFI and improved G:F of growing pigs when increasing the DE density of the diets through changes in dietary composition, but inconsistent responses (increased in Exp. 1, but not changed in Exp.2) in ADG were observed. Quiniou and Noblet (2012) reported a linear reduction in ADFI and increased ADG and G:F in pigs fed diets with increased concentration of dietary NE from 1,935 to 2,651 kcal/kg. In the present study, ADFI, ADG, and G:F did not differ among pigs fed LOW, MH, and HIGH diets with a maximum difference of 94 kcal/kg in dietary NE content (maximum difference of 235 kcal/kg among NE of DDGS A, C, and D; Table 3.6). It appears that feeding DDGS sources with NE content greater than 2,300 kcal/kg may result in similar growth performance of growing-finishing pigs, but reduced performance can be expected when DDGS contains less than 2,000 kcal/kg NE. In addition, dietary fiber concentration may have also affected ADFI, because increased bulkiness of fiber may limit the physical gut capacity of pigs to consume more feed. However, the ability of pigs to maintain energy intake from fiber-rich diets appears to be related to their physiological age (Kennelly and Aherne, 1980). Studies have reported limited ADFI of pigs fed 40% or greater levels of DDGS in early feeding phases (Hardman, 2013; Wu, chapter 2). Therefore, it is likely that the "gut fill" effect of dietary DDGS has prevented pigs fed ML to overcome the negative impact of low dietary energy on ADG by increasing feed intake in periods 1 to 3. Whereas, pigs fed ML were able to maintain greater ADFI and ADG than pigs fed other diets in the late feeding periods when gut capacity of pigs was improved with increased

BW. This finding may explain the dietary treatment × period interactions observed for ADFI and ADG.

Studies have shown less prominent effects of variable dietary NE content on carcass characteristics compared with growth performance criteria. Kerr et al. (2003) reported that pigs had similar HCW, LMA, 10th rib fat thickness, and FFL% when fed diets with a difference of about 100 kcal/kg (as-fed) in dietary NE content. Quiniou and Noblet (2012) also reported that HCW, BF thickness, and carcass yield were not affected when differences in dietary NE were less than 286 kcal/kg. In the present study, although overall ADG responses varied among treatments, pigs fed DDGS sources with up to a 688 kcal/kg difference in NE content, thus about a 275 kcal/kg difference in dietary NE, had no discernible differences in HCW, carcass yield, BF depth, LMA, and FFL%. The use of the NRC (2012) model to calculate dietary NE using observed G:F responses relies on the assumption that the effect of variable NE intake on G:F was not affected by the differences in deposition of energy in carcass fat or lean. This assumption was tested by comparing the 2 sets of carcass composition data measured using ultrasound at the end of the grower and finisher periods, which showed similar increases in BF depth and LMA among dietary treatments.

Net energy content of DDGS

To achieve the goal of obtaining DDGS sources with variable NE content, predicted NE content of DDGS was provided by ILLUMINATE® at the beginning of the present study (Table 3.6). According to the ILLUMINATE® estimates, NE content of DDGS sources A, B, C, and D gradually increased with an interval of about 220 kcal/kg. When included in diets at 40%, final dietary NE concentration increased about 90 kcal/kg

with each DDGS source. We hypothesized that if the NE values were predicted precisely, pigs would display linearly decreased ADFI and linearly increased G:F in pigs fed LOW, ML, MH, and HIGH treatments, respectively. However, we observed an increased ADFI and reduced G:F from pigs fed ML, but similar growth responses among pigs fed LOW, MH, and HIGH. Based on these results, our NRC (2012) model calculations suggested that the ILLUMINATE® NE estimates for DDGS B and D were overestimated slightly by 331 and 230 kcal/kg, respectively, and NE estimates of DDGS A and C were underestimated slightly by 294 and 143 kcal/kg, respectively. Nevertheless, the ILLUMINATE® NE prediction still resulted in the lowest prediction bias and a moderate error compared with other approaches to estimate NE (Table 3.6).

Compared with published values from NRC (2012), NE of DDGS C and D determined by the NRC (2012) model calculation in this experiment were greater than the value (2,384 kcal/kg) for DDGS with > 10% oil, and the NE content of DDGS B was lower compared with the value (2,009 kcal/kg) for DDGS with < 4% oil. Gutierrez el al. (2014) determined NE values of 2 DDGS sources using the comparative slaughter method; low-oil DDGS source with 2.6% EE contained less NE value (1,860 kcal/kg) than DDGS B, and NE concentration of the conventional DDGS source (2,187 kcal/kg) with 13% EE was also lower compared with the DDGS sources A, C, and D evaluated in the present study. Similarly, NE content of 6 DDGS sources (ranging from 2,012 to 2,298 kcal/kg) determined by Kerr et al. (2015) using the dual energy X-ray absorptiometry method was lower than the NE values for DDGS sources A, C, and D, but was slightly greater than source B. In addition, Graham et al. (2014b) also reported a large variation in NE values among 5 DDGS sources (ranging from 2,122 to 2,893 kcal/kg), which were

slightly greater than the range in NE content among DDGS sources evaluated in the current study. These observations indicate that there is considerable variability of NE content among DDGS sources, and different methodologies may also contribute to this variation. Increased risk of inaccurate diet formulation can be expected if static NE loading values are used when formulating diets containing DDGS.

To compare the NE estimations, we determined precision (measured by PE) that refers to the repeatability of an equation for different observations, and accuracy (measured by prediction bias) that refers to the proximity of predicted estimates to the true or observed values. Among the Noblet et al. (1994b) equations, precision and accuracy were improved when using DE content (equations 4 and 5) as a predictor variable compared with using ME content (equations 7 and 8). This result is mainly explained by the accumulation of error associated with using predicted DE value in the calculation of ME content. In addition, if predicting NE of DDGS directly from chemical composition, crude fiber (equation 9) may be a better predictor variable than ADF and NDF contents (equations 10 and 11, respectively). However, the Noblet et al. (1994b) equations were derived from complete feeds consisting of high starch and low fiber contents. Therefore, these equations may not sufficiently consider the nature of dietary fiber and composition of lipid (Noblet et al., 1994b), which may have caused the underestimation of NE for DDGS sources C and D. Finally, although the equation developed by Graham et al. (2014b) is designed for use in DDGS and is based on the EE concentration of DDGS, it contains substantially large PE and bias, which suggests that using EE as the only predictor variable may not adequately estimate NE content of DDGS.

In summary, growing-finishing pigs fed diets containing 40% DDGS with reduced NE content are likely to have increased ADFI and reduced ADG and G:F, but differences in carcass characteristics cannot be detected when the difference of NE content is less than 700 kcal/kg among DDGS sources (approximately 275 kcal/kg difference in dietary NE). In addition, current NE prediction equations and commercial estimates from ILLUMINATE® result in suboptimal prediction of NE content among DDGS sources evaluated in this study. Revision is needed to achieve better predictions among DDGS sources that contain low oil concentration.

Table 3.1. Nutrient composition and physical characteristics of feed ingredients (as-fed basis)

	DDGS[1]					
Item	A	B	C	D	Corn	Soybean meal
DM, %	87.44	88.18	89.60	89.00	87.43	88.18
CP, %	25.82	28.17	26.84	27.04	7.25	47.76
Ether extract, %	10.70	5.61	14.19	15.98	2.90	0.26
Crude fiber, %	8.15	8.81	8.54	9.29	2.46	3.52
Ash, %	4.38	5.26	3.91	4.56	1.11	6.35
ADF, %	16.23	9.70	13.72	11.73	3.75	6.40
NDF, %	26.03	22.99	28.11	22.98	8.51	7.15
Ca, %	0.03	0.09	0.02	0.02	0.002	0.34
P, %	0.75	0.81	0.66	0.81	0.18	0.58
Starch, %	3.30	7.54	3.46	2.25	61.90	0.88
Particle size, μm	580	390	620	380	-	-
Essential AA, %						
Arg	1.17	1.29	1.24	1.24	0.33	3.46
His	0.77	0.85	0.82	0.78	0.22	1.33
Ile	1.05	1.10	1.08	1.11	0.24	2.19
Leu	2.95	3.16	3.16	3.21	0.82	3.74
Lys	0.84	0.98	0.98	0.90	0.25	3.17
Met	0.52	0.59	0.52	0.50	0.17	0.68
Phe	1.26	1.30	1.32	1.35	0.33	2.41
Thr	1.08	1.13	1.11	1.11	0.27	1.89
Trp	0.18	0.19	0.18	0.19	0.05	0.67
Val	1.33	1.38	1.37	1.40	0.34	2.25
Non-essential AA, %						
Ala	1.69	1.90	1.85	1.86	0.51	2.06
Asp	1.59	1.81	1.71	1.69	0.54	5.45
Cys	0.48	0.60	0.52	0.51	0.16	0.69
Glu	2.85	3.93	3.46	3.31	1.26	8.53
Gly	1.00	1.12	1.06	1.05	0.29	2.02
Hyl	0.26	0.15	0.20	0.25	0.02	0.06
Hyp	0.21	0.08	0.10	0.15	0.03	0.04
Orn	0.06	0.06	0.06	0.06	0.01	0.06
Pro	1.71	2.13	1.90	1.87	0.61	2.46
Ser	1.18	1.24	1.22	1.23	0.34	2.07
Tau	0.06	0.07	0.07	0.07	0.11	0.12
Tyr	0.86	0.94	0.91	0.89	0.18	1.67
NE[2], kcal/kg	2,083	2,255	2,469	2,743	2,672	2,087

[1] Selected sources of distillers dried grains with solubles with increasing concentrations of predicted NE estimated by a commercial service (ILLUMINATE®; Nutriquest, Mason City, IA).

[2] Predicted NE values from ILLUMINATE® for DDGS sources and recommended NE values from NRC (2012) for corn and soybean meal (dehulled, solvent extracted).

Table 3.2. Diet composition, phase 1 and 2 (as-fed basis)

	Phase 1 (22 to 50 kg BW)				Phase 2 (50 to 75 kg BW)			
Item	LOW[1]	ML[1]	MH[1]	HIGH[1]	LOW	ML	MH	HIGH
Ingredients, %								
Corn	36.42	36.41	36.40	36.41	44.10	44.10	44.09	44.10
Soybean meal	20.59	20.59	20.59	20.59	13.52	13.52	13.52	13.52
DDGS	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00
Limestone	1.62	1.60	1.55	1.62	1.40	1.45	1.30	1.39
Monocalcium P (21% P)	0.51	0.48	0.57	0.37	0.17	0.17	0.28	0.08
Salt	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
VTM premix[2]	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
L-Lys HCl	0.21	0.17	0.22	0.33	0.15	0.10	0.14	0.24
DL-Met	-	-	-	0.01	-	-	-	-
L-Thr	-	0.09	-	-	-	-	-	-
L-Trp	-	0.01	0.02	0.02	0.01	0.01	0.02	0.02
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Calculated composition								
NE[3], kcal/kg	2,176	2,246	2,331	2,445	2,236	2,303	2,390	2,503
CP, %	23.01	23.98	23.43	23.63	20.14	21.04	20.54	20.72
Ca, %	0.79	0.80	0.77	0.76	0.62	0.67	0.60	0.60
Total P, %	0.59	0.61	0.57	0.59	0.49	0.52	0.48	0.50
STTD[4] P, %	0.36	0.37	0.35	0.35	0.28	0.30	0.28	0.28
Ca : STTD P	2.14	2.11	2.14	2.11	2.14	2.16	2.07	2.07
Total Lys, %	1.25	1.27	1.31	1.37	1.00	1.01	1.04	1.09
SID[5] AA, %								
Lys	1.04	1.07	1.11	1.16	0.81	0.84	0.87	0.90
Met	0.34	0.38	0.34	0.34	0.30	0.35	0.31	0.29
Met + Cys	0.63	0.74	0.67	0.66	0.57	0.68	0.60	0.59
Thr	0.73	0.86	0.75	0.76	0.63	0.68	0.66	0.66
Trp	0.18	0.18	0.19	0.20	0.14	0.15	0.15	0.16
SID Lys/NE, g/kcal	4.78	4.76	4.76	4.74	3.62	3.65	3.64	3.60
Analyzed composition								
DM, %	87.38	87.59	87.67	87.96	87.06	86.94	87.35	87.56
CP, %	23.42	23.98	23.40	24.07	19.89	21.00	20.76	20.77
Ether extract, %	4.76	2.84	5.84	6.26	5.04	3.04	5.93	6.73
Crude fiber, %	4.86	4.72	4.81	4.37	4.89	4.56	4.97	4.70
ADF, %	8.50	6.09	7.63	7.40	8.33	6.04	6.73	6.83
NDF, %	14.22	13.97	15.92	14.40	14.96	14.16	16.28	14.17
Ca, %	0.85	0.71	0.73	0.79	0.75	0.56	0.57	0.55
P, %	0.67	0.61	0.57	0.56	0.50	0.51	0.48	0.51
AA, %								
Lys	1.29	1.12	1.27	1.34	0.97	1.00	0.94	0.99
Thr	0.94	0.93	0.94	0.89	0.80	0.79	0.75	0.76
Trp	0.24	0.27	0.26	0.26	0.21	0.21	0.22	0.23
Met	0.42	0.38	0.37	0.40	0.36	0.39	0.34	0.31

[1] LOW = diet containing 40% distillers dried grains with solubles (DDGS) source A with low predicted NE (2,083 kcal/kg); ML = diet containing 40% DDGS source B with medium-low predicted NE (2,255 kcal/kg); MH = diet containing 40% DDGS source C with medium-high

predicted NE (2,469 kcal/kg); and HIGH = diet containing 40% DDGS source D with high predicted NE (2,743 kcal/kg).

[2] VTM premix = vitamin-trace mineral premix, which provided the following nutrients per kg of diet: 8,818 IU vitamin A, 1,654 IU vitamin D_3, 33 IU vitamin E, 3.3 mg vitamin K, 5.5 mg riboflavin, 33.1 mg niacin, 22.0 mg pantothenic acid, 0.03 mg vitamin B_{12}, 0.3 mg iodine as ethylenediamine dihydroiodide, 0.3 mg selenium as sodium selenite, 55.1 mg zinc as zinc oxide, 33.1 iron as ferrous sulfate, 5.5 mg manganese as manganous oxide, and 3.9 mg copper as copper sulfate.

[3] Calculated NE content of diets based on diet formulation; NRC (2012) recommended NE values were used for corn and soybean meal (dehulled, solvent extracted), and NE estimates from ILLUMINATE® (Nutriquest, Mason City, IA) were used for DDGS sources.

[4] STTD = standardized total tract digestible.

[5] SID = standardized ileal digestible. Coefficients for AA digestibility were determined by equations from Almeida et al. (2013) for DDGS, and NRC (2012) recommended coefficients were used for corn and soybean meal.

Table 3.3. Diet composition, phase 3 and 4 (as-fed basis)

	Phase 3 (75 to 100 kg BW)				Phase 4 (100 to 115 kg BW)				
Item	LOW[1]	ML[1]	MH[1]	HIGH[1]	LOW	ML	MH	HIGH	Holding[1]
Ingredients, %									
Corn	47.77	47.76	47.77	47.76	49.57	49.58	49.58	49.58	80.75
Soybean meal	10.01	10.01	10.01	10.01	8.25	8.25	8.25	8.25	16.72
DDGS	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	-
Limestone	1.34	1.39	1.29	1.38	1.34	1.38	1.27	1.38	0.96
Monocalcium P (21% P)	0.10	0.12	0.17	-	0.11	0.13	0.21	0.01	0.92
Salt	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
VTM premix[2]	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
L-Lys HCl	0.12	0.06	0.09	0.18	0.07	-	0.03	0.12	-
L-Trp	0.01	0.01	0.02	0.02	0.01	0.01	0.01	0.01	-
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Calculated composition									
NE[3], kcal/kg	2,262	2,328	2,415	2,528	2,272	2,339	2,426	2,538	2,403
CP, %	18.70	19.58	19.08	19.25	17.93	18.82	18.32	18.48	13.84
Ca, %	0.57	0.62	0.56	0.57	0.57	0.62	0.56	0.56	0.58
Total P, %	0.47	0.49	0.45	0.47	0.46	0.49	0.45	0.46	0.44
STTD[4] P, %	0.26	0.28	0.25	0.26	0.26	0.28	0.25	0.25	0.27
Ca : STTD P	2.16	2.18	2.20	2.16	2.16	2.18	2.20	2.20	2.15
Total Lys, %	0.87	0.88	0.90	0.94	0.77	0.78	0.80	0.84	0.73
SID[5] AA, %									
Lys	0.69	0.71	0.74	0.77	0.60	0.62	0.64	0.67	0.62
Met	0.29	0.33	0.29	0.28	0.28	0.32	0.28	0.27	0.21
Met + Cys	0.54	0.64	0.57	0.55	0.52	0.63	0.56	0.54	0.41
Thr	0.58	0.63	0.61	0.61	0.56	0.60	0.58	0.58	0.44
Trp	0.12	0.13	0.13	0.14	0.11	0.11	0.12	0.12	0.14
SID Lys/NE, g/kcal	3.05	3.05	3.06	3.05	2.64	2.65	2.64	2.64	2.58
Analyzed composition									
DM, %	87.12	87.19	87.63	87.60	86.75	87.64	87.51	87.29	87.41
CP, %	18.70	19.23	19.00	19.03	17.06	19.15	18.72	18.03	12.13
Ether extract, %	4.99	3.04	5.93	6.68	5.09	3.31	6.09	6.76	2.14
Crude fiber, %	5.04	4.53	4.58	4.39	4.71	4.37	4.49	4.37	4.63
ADF, %	8.26	5.56	7.20	7.19	8.28	5.89	7.03	6.53	3.40
NDF, %	16.43	14.19	16.55	15.02	16.21	13.97	16.29	14.08	9.17
Ca, %	0.64	0.80	0.63	0.52	0.77	0.66	0.58	0.64	0.56
P, %	0.46	0.49	0.47	0.48	0.45	0.60	0.41	0.50	0.37
AA, %									
Lys	0.81	0.85	0.82	0.96	0.74	0.78	0.79	0.87	0.72
Thr	0.71	0.76	0.73	0.76	0.68	0.74	0.71	0.73	0.51
Trp	0.21	0.21	0.21	0.22	0.20	0.19	0.18	0.19	0.15
Met	0.33	0.36	0.32	0.36	0.33	0.36	0.33	0.34	0.22

[1] LOW = diet containing 40% distillers dried grains with solubles (DDGS) source A with low predicted NE (2,083 kcal/kg); ML = diet containing 40% DDGS source B with medium-low predicted NE (2,255 kcal/kg); MH = diet containing 40% DDGS source C with medium-high predicted NE (2,469 kcal/kg); HIGH = diet containing 40% DDGS source D with high predicted NE (2,743 kcal/kg); and Holding = corn-soybean meal diet fed to pigs 5 days prior to slaughter due to depletion of DDGS.

[2] VTM premix = vitamin-trace mineral premix, which provided the following nutrients per kg of diet: 8,818 IU vitamin A, 1,654 IU vitamin D_3, 33 IU vitamin E, 3.3 mg vitamin K, 5.5 mg riboflavin, 33.1 mg niacin, 22.0 mg pantothenic acid, 0.03 mg vitamin B_{12}, 0.3 mg iodine as ethylenediamine dihydroiodide, 0.3 mg selenium as sodium selenite, 55.1 mg zinc as zinc oxide, 33.1 iron as ferrous sulfate, 5.5 mg manganese as manganous oxide, and 3.9 mg copper as copper sulfate.

[3] Calculated NE content of diets based on diet formulation; NRC (2012) recommended NE values were used for corn and soybean meal (dehulled, solvent extracted), and NE estimates from ILLUMINATE® (Nutriquest, Mason City, IA) were used for DDGS sources.

[4] STTD = standardized total tract digestible.

[5] SID = standardized ileal digestible. Coefficients for AA digestibility were determined by equations from Almeida et al. (2013) for DDGS, and NRC (2012) recommended coefficients were used for corn and soybean meal.

Table 3.4. Effects of dietary distillers dried grains with solubles (DDGS) with variable NE content on growth performance of growing-finishing pigs

	40% DDGS				
Item	LOW[1]	ML[1]	MH[1]	HIGH[1]	SEM
No. Pens	12	12	12	12	
BW, kg					
Initial	22.0	22.0	21.9	21.9	1.98
Period 1	44.5	43.3	44.8	44.5	2.07
Period 2	58.5	56.4	58.7	57.6	2.15
Period 3	72.8	70.0	72.9	71.5	2.19
Period 4	87.2	83.5	86.7	85.2	2.28
Period 5	99.0	95.3	98.8	97.2	2.31
Final	112.2	109.6	112.7	110.8	2.20
P-value					
Diet			0.846		
Phase			< 0.01		
Diet × period			< 0.01		
ADFI, kg					
Period 1	1.54	1.54	1.49	1.49	0.06
Period 2	2.27	2.31	2.23	2.17	0.06
Period 3	2.69	2.70	2.56	2.52	0.06
Period 4	2.82^{ab}	2.87^{b}	2.68^{ac}	2.63^{c}	0.06
Period 5	2.78^{a}	2.97^{b}	2.71^{a}	2.67^{a}	0.06
Period 6	3.06^{a}	3.38^{b}	3.03^{a}	2.98^{a}	0.07
Overall	2.53^{ab}	2.63^{a}	2.45^{b}	2.41^{b}	0.06
P-value					
Diet			0.053		
Phase			< 0.01		
Diet × period			< 0.01		
ADG, kg					
Period 1	0.81^{ab}	0.76^{a}	0.82^{b}	0.81^{ab}	0.02
Period 2	0.99^{a}	0.94^{b}	0.99^{ab}	0.94^{b}	0.02
Period 3	1.04^{a}	0.97^{b}	1.01^{ab}	0.99^{ab}	0.02
Period 4	1.03^{a}	0.97^{b}	0.99^{ab}	0.97^{b}	0.02
Period 5	0.87	0.84	0.86	0.86	0.02
Period 6	0.88^{a}	0.95^{bc}	0.97^{c}	0.89^{ab}	0.03
Overall	0.93^{ab}	0.90^{a}	0.94^{b}	0.91^{ab}	0.01
P-value					
Diet			0.121		
Phase			< 0.01		
Diet × period			0.075		
G:F					
Period 1	0.524^{a}	0.498^{c}	0.552^{b}	0.545^{ab}	0.008

Period 2	0.440[a]	0.410[b]	0.448[a]	0.437[a]	0.008
Period 3	0.388[a]	0.362[b]	0.401[a]	0.397[a]	0.008
Period 4	0.365[a]	0.337[b]	0.368[a]	0.370[a]	0.008
Period 5	0.305[a]	0.282[b]	0.319[a]	0.323[a]	0.008
Period 6	0.280	0.277	0.303	0.294	0.010
Overall	0.384[a]	0.361[b]	0.398[a]	0.394[a]	0.006
P-value					
Diet		< 0.01			
Phase		< 0.01			
Diet × period		0.484			

[1] LOW = diet containing 40% distillers dried grains with solubles (DDGS) source A with low predicted NE (2,083 kcal/kg); ML = diet containing 40% DDGS source B with medium-low predicted NE (2,255 kcal/kg); MH = diet containing 40% DDGS source C with medium-high predicted NE (2,469 kcal/kg); and HIGH = diet containing 40% DDGS source D with high predicted NE (2,743 kcal/kg).

[abc] Means with different superscripts within a row differ ($P < 0.05$).

Table 3.5. Effects of dietary distillers dried grains with solubles (DDGS) with variable NE content on carcass characteristics

	40% DDGS					
Item	LOW[1]	ML[1]	MH[1]	HIGH[1]	SEM	*P*-value
HCW, kg	76.70	75.05	76.82	75.56	1.08	0.59
Carcass yield, %	69.57	69.51	69.77	69.43	0.19	0.63
BF depth[2], (75 kg), mm	12.03	11.79	12.12	12.49	0.30	0.19
BF depth[3] (109 kg), mm	16.48	16.34	16.71	17.06	0.35	0.34
LM area[2] (75kg), cm^2	30.20	30.05	30.69	30.80	0.84	0.35
LM area[3] (109 kg), cm^2	43.35	44.32	44.26	44.47	0.47	0.31
Fat-free lean[5], %	54.35	54.80	54.52	54.54	0.27	0.65

[1] LOW = diet containing 40% distillers dried grains with solubles (DDGS) source A with low predicted NE (2,083 kcal/kg); ML = diet containing 40% DDGS source B with medium-low predicted NE (2,255 kcal/kg); MH = diet containing 40% DDGS source C with medium-high predicted NE (2,469 kcal/kg); and HIGH = diet containing 40% DDGS source D with high predicted NE (2,743 kcal/kg).

[2] Backfat depth or LM area measured by real-time ultrasound at the end of growing phase (average BW = 75 kg). Body weight measured at the end of growing phase was used as a covariate in the statistical analysis.

[3] Backfat depth or LM area measured by real-time ultrasound at the end of finishing phase (average BW = 109 kg). Final BW was used as a covariate in the statistical analysis.

Table 3.6. Calculation and evaluation of predicted energy content for 4 sources of dietary distillers dried grains with solubles (DDGS; as-fed basis)

Item	Equation	A[1]	B[1]	C[1]	D[1]	PE[2]	Bias
GE[3], kcal/kg	-	4,578	4,406	4,814	4,809	-	-
DE[4], kcal/kg	-2,161 + (1.39 × GE) – (20.7 × NDF) – (49.3 × ether extract)	3,408	3,466	3,473	3,498	-	-
ME[4], kcal/kg	-261 + (1.05 × DE) – (7.89 × CP) + (2.47 × NDF) – (4.99 × ether extract)	3,157	3,215	3,200	3,204	-	-
NE, kcal/kg							
Model calculation[5]	-	2,377	1,924	2,612	2,513	-	-
ILLUMINATE®	-	2,083	2,255	2,469	2,743	259.2	31.2
Noblet et al. (1994b)[6]							
Equation 4	(0.703 × DE) + (1.58 × ether extract) + (0.47 × starch) – (0.97 × CP) – (0.98 × crude fiber)	2,246	2,193	2,335	2,366	216.7	-71.1
Equation 5	(0.700 × DE) + (1.61 × ether extract + (0.48 × starch) – (0.91 × CP) – (0.87 × ADF)	2,194	2,204	2,309	2,366	237.2	-88.1
Equation 7	(0.730 × ME) + (1.31 × ether extract) + (0.37 × starch) – (0.67 × CP) – (0.97 × crude fiber)	2,202	2,168	2,269	2,284	255.0	-125.4
Equation 8	(0.726 × ME) + (1.33 × ether extract) + (0.39 × starch) – (0.62 × CP) – (0.83 × ADF)	2,149	2,177	2,242	2,281	276.7	-144.0
Equation 9	2,796 + (4.15 × ether extract) + (0.81 × starch) – (7.07 × ash) – (5.38 × crude fiber)	2,161	1,900	2,381	2,344	179.5	-159.8
Equation 10	2,790 + (4.12 × ether extract) + (0.81 × starch) – (6.65 × ash) – (4.72 × ADF)	1,844	1,931	2,199	2,299	353.6	-288.0
Equation 11	2,875 + (4.38 × ether extract) + (0.67 × starch) – (5.50 × ash) – [2.01 × (NDF – ADF)] – (4.02 × ADF)	1,909	1,874	2,160	2,322	339.6	-290.0
Graham et al. (2014b)[7]							
NE equation	(115.011 × ether extract) + 1,501.01	2,543	1,969	2,977	3,174	387.0	309.3

[1] Sources of DDGS selected based on NE estimates from a commercial service (ILLUMINATE®; Nutriquest, Mason City, IA).
[2] Prediction error.
[3] Determined GE using bomb calorimetry.
[4] Anderson et al. (2012).
[5] Back-calculated NE using the NRC (2012) growth model based on observed G:F.
[6] Energy values expressed as kcal/kg and composition expressed as g/kg DM
[7] Energy values expressed as kcal/kg and composition expressed as % DM

CHAPTER 4

Pork fat quality of pigs fed distillers dried grains with solubles with variable oil content and evaluation of iodine value prediction equations

Summary

Back, belly, and jowl fat samples of pigs fed 4 sources of distillers grains with solubles (DDGS) were utilized to determine the impact of feeding DDGS with variable oil content on pork fat quality, and to evaluate the precision and accuracy of published iodine value (IV) prediction equations. Barrows (n = 432) were blocked by initial BW (22.0 ± 4.3 kg), and within blocks, pens were randomly allotted to 1 of 4 dietary treatments (9 pigs/pen, 12 replicates/treatment). Dietary treatments consisted of 4 corn and soybean meal based diets containing 40% DDGS from different sources with 10.7, 5.6, 14.2, or 16.0% ether extract (EE; as-fed) content. Diets did not contain any other supplemental lipid sources and were formulated to meet or exceed NRC (2012) nutrient requirements. Carcass fat samples were collected from 2 pigs/pen with final BW closest to the pen average. Regardless of fat depot, SFA content (g/100 g fat) of pigs fed 5.6% EE DDGS (35.4) was greater ($P < 0.05$) than pigs fed 14.2 or 16.0% EE DDGS sources (34.4 and 30.2, respectively), and tended to be greater ($P < 0.10$) than pigs fed 10.7% EE DDGS (34.6). Pigs fed 10.7 and 14.2% EE DDGS had greater ($P < 0.01$) SFA concentration than pigs fed 16.0% EE DDGS. Regardless of fat depot, MUFA content (g/100 g fat) of pigs fed 10.7, 5.6, and 14.2% DDGS sources were similar (43.7, 43.1, and 43.0, respectively), but were greater ($P < 0.01$) than that of pigs fed 16.0% EE DDGS (40.0). Dietary treatment × fat depot interaction was observed for PUFA ($P < 0.05$) and IV ($P = 0.079$). Pigs fed 10.7, 5.6, and 14.2% DDGS sources had reduced ($P < 0.01$)

PUFA concentration and IV compared with pigs fed 16.0% EE DDGS, but the magnitude of responses in PUFA and IV to the variable oil content of DDGS was greater in backfat than in belly and jowl fat. Carcass fat IV data from pigs fed diets containing another 4 sources of DDGS from a previous experiment were combined with current dataset to evaluate prediction error (PE) and bias of published carcass fat IV prediction equations. Equations using dietary C18:2 content or IV product as a single predictor resulted in highly variable PE (g/100g) ranging from 3.43 to 8.36, and bias (g/100g) ranging from -5.05 to 5.66. Using equations that included additional diet composition information and pig growth performance factors decreased PE (3.27 to 4.73) and bias (-3.37 to 1.73) of prediction for backfat, compared with equations only based on the characteristics of dietary lipid, but this improvement was limited in the prediction for belly and jowl fat. Predictions based on percentage of DDGS in diets had the greatest PE (6.66 to 9.19) and bias (5.53 to 8.00). In conclusion, reduced oil content of DDGS may alleviate the negative impact of feeding DDGS on pork fat quality. Published equations have variable PE and bias when predicting carcass fat IV. Predictions that include additional dietary and pig performance factors may be more accurate and precise than predictions based only on the characteristics and quantities of dietary lipids, and using the percentage of DDGS in diet results in the poorest prediction.

Key words: DDGS, iodine value, pork fat quality, prediction equations

Introduction

Corn distillers dried grains with solubles (**DDGS**) have been used widely in swine diets as a cost effective source of energy and AA. However, reduction in saturation and firmness of carcass fat has been commonly observed when more than 20% DDGS are

added in growing-finishing diets (Benz et al., 2010; Xu et al., 2010a; Graham et al., 2014a,b). This reduction in pork fat quality is the result of a high concentration of unsaturated fatty acids, mainly linoleic acid, in DDGS. Traditional DDGS sources contain more than 10% crude fat (Stein and Shurson, 2009), but in recent years, most ethanol plants have been extracting corn oil and producing DDGS with a greater variation in oil content (5 to 12%; Kerr et al., 2013). Researchers have suggested that decreased oil content alleviates the negative effects of feeding DDGS on pork fat quality (Graham et al., 2014b), but the magnitude of this improvement has not been compared among different DDGS sources. In addition, fatty acid (**FA**) composition of carcass fat varies among anatomical sites because of different rates of development (Lizardo et al., 2002) and activities of lipogenic enzymes in adipose tissue (Mourot et al., 1995). Thus, we hypothesize that changes in FA composition in response to the reduction of oil in DDGS may also differ among carcass fat depots.

Iodine value (**IV**) is a measurement of unsaturation of FA, and is used currently as a quality standard for evaluating pork fat firmness. Packing plants have established maximum acceptance of carcass fat IV ranging from 70 to 75 g/100g (Benz et al., 2011a). As a result, accurate prediction of carcass fat IV becomes essential for producers to maximize the utilization of DDGS in growing-finishing diets while maintaining acceptable pork fat quality. Equations have been developed to predict IV of carcass fat depots based on the composition and amount of dietary lipids consumed, as well as pig growth performance. However, precision and accuracy of these equations have not been evaluated to identify the equation with the greatest utility. Therefore, the objectives of this study were to determine the effects of feeding 4 sources of DDGS with variable oil

content on FA composition of carcass fat, and to use the observed IV to evaluate selected IV prediction equations for backfat, jowl, and belly fat.

Materials and methods

All experimental procedures in this study were approved by the University of Minnesota Institutional Animal Care and Use Committee (St. Paul, MN).

Animals and diets

Barrows (n = 432) were blocked by initial BW (22.0 ± 4.3 kg) and allotted to 12 blocks (4 pens/block; 9 pigs/pen). Within blocks, pens were allotted randomly to 1 of 4 dietary treatments (12 replicates/treatment). Dietary treatments consisted of 4 corn and soybean meal based diets containing 40% DDGS from different sources that contained 10.7, 5.6, 14.2, or 16.0% ether extract (**EE**; as-fed). Experimental procedures for animal management and dietary treatment were described in chapter 3. Diets containing 10.7, 5.6, 14.2, and 16.0% EE DDGS sources used in this study refer to the dietary treatments "LOW", "ML", "MH", and "HIGH" (dietary NE concentrations varied from low to high), respectively, defined in chapter 3.

Sample collection

Samples of backfat (**BF**), belly, and jowl fat were collected from 2 pigs/pen with final BW closest to the pen average at the end of the experiment. All fat samples were obtained from the left side of carcasses. Backfat samples (n = 96) were collected from the midline opposite the last rib and included all 3 fat layers. Belly fat samples (n = 96) were collected from the midline opposite the last rib on the teat side of the belly, and jowl fat samples (n = 96) were obtained from the anterior tip of the jowl. Samples were packaged in Whirlpac® sample bags, stored in a cooler with dry ice, and delivered to the University

of Minnesota Swine Nutrition Laboratory within 2 h after collection. All fat samples were frozen with dry ice during transportation to the University of Missouri Agricultural Experiment Station Chemical Laboratory (**AESCL**; Columbia, MO) for analysis of fatty acid profile.

Chemical analysis and calculations

Fatty acid profile (Method 996.06; AOAC 2006) was determined at AESCL for 4 DDGS samples (Table 4.1), 17 complete diets (Table 4.2), and 288 carcass fat samples. Iodine value was calculated using the following equation (AOCS, 1998): IV =[C16:1] × 0.95 + [C18:1] × 0.86 + [C18:2] × 1.732 + [C18:3] × 2.616 + [C20:1] × 0.785 + [C22:1] × 0.723, where brackets indicate concentration. Iodine value product (**IVP**) of diets was calculated using: IVP = dietary IV × % dietary lipids × 0.10 (Madsen et al., 1992).

Statistical analysis

Statistical analysis was conducted using the MIXED procedure (SAS Inst. Inc., Cary, NC) with pen as the experimental unit. Fatty acid profile and IV of carcass fat samples were analyzed in a split plot design, with diet as the whole plot and fat depot as the subplot. The dietary treatment × depot interaction was also included in the final statistical analysis. Means were reported as least-squares means and were separated by the PDIFF option when $P < 0.05$, and trends are reported when $0.05 < P < 0.10$.

Evaluation of IV predictions

Carcass fat IV data of pigs fed corn and soybean meal based control diets, along with IV data from pigs fed 3 different sources of DDGS with variable oil content in a previous experiment (chapter 2), were combined with the current dataset to evaluate the precision and accuracy of 18 selected prediction equations. In the previous experiment,

pigs were fed a corn-soybean meal based control diet or 3 diets containing 40% DDGS with low (5.9% EE), medium (9.9% EE), or high (14.2% EE) oil concentrations. This experiment was conducted in the same facility with the same genetic line of pigs, and followed the same experimental procedures as used in the present study.

Predicted IV of pigs fed each dietary treatment was calculated using 8 published equations (Eq. 1 to 8; Table 4.3) for backfat, 5 equations (Eq. 9 to 13) for jowl fat, 3 equations (Eq. 14 to 16) for belly fat, and 2 equations (Eq. 17 and 18) for the average of the 3 fat depots. Linoleic acid (C18:2) concentration and IVP of each dietary treatment was calculated as the average among feeding phases and weighted for total feed consumption within each phase. Estimates of IV from prediction equations were compared with the observed IV (least-squares means; Table 4.4) determined by analyzed FA composition for each carcass fat depot of pigs fed in the 2 experiments. Standard error of prediction (prediction error; **PE**) and prediction bias were calculated using following equations:

$$PE = \sqrt[2]{\frac{1}{n}\sum_{i=1}^{n}(yi - \hat{y}i)^2}$$

and

$$Bias = \frac{1}{n}\sum_{i=1}^{n}(yi - \hat{y}i)$$

, where y_i is the predicted IV for the ith observation, $\hat{y}_i$ is the observed IV for the ith observation, and n is the total number of observations (Lane et al, 2014).

Results and discussion

Pork fat quality

No dietary treatment × depot interactions were observed for SFA or MUFA (Table 4.4). Regardless of fat depot, SFA content (g/100g fat) of pigs fed 5.6% EE DDGS (35.4) was greater ($P < 0.05$) than for pigs fed 14.2 and 16.0% EE DDGS (34.4 and 30.2, respectively) and tended ($P < 0.10$) to be greater for pigs fed 10.7% EE DDGS (34.6). Concentrations of SFA in pigs fed 10.7 and 14.2% EE DDGS were not different, but were greater ($P < 0.01$) than those fed 16.0% EE DDGS. Among fat depots, BF and belly fat had similar SFA content (35.3 and 34.8, respectively), but were greater ($P < 0.01$) than that of jowl fat (30.8). Pigs fed 10.7, 5.6, and 14.2% EE DDGS sources had similar MUFA content (43.7, 43.1, and 43.0, respectively), but was greater ($P < 0.01$) than that of pigs fed 16.0% EE DDGS (40.0). Among fat depots, BF (40.6) contained less ($P < 0.01$) concentration of MUFA than belly and jowl fat (42.8 and 43.9, respectively), and MUFA content of belly fat was lower ($P < 0.01$) than for jowl fat.

There were dietary treatment × depot interactions ($P < 0.05$) for C18:2 and PUFA content. In both belly and jowl fat, C18:2 content in pigs fed 10.7, 5.6, and 14.2% EE DDGS were similar, but lower ($P < 0.01$) than that for pigs fed 16.0% EE DDGS. For BF, pigs fed 16.0% EE DDGS had a increased ($P < 0.01$) C18:2 content compared with the other dietary treatments. Concentration of C18:2 in BF of pigs fed 14.2% EE DDGS was greater ($P < 0.01$) than for pigs fed 5.6% EE DDGS, but not different from those fed 10.7% EE DDGS, and there was no difference among pigs fed 10.7 and 5.6% EE DDGS. Among fat depots, concentrations of C18:2 in BF and jowl fat were not different, but they were greater ($P < 0.05$) than belly fat in pigs fed 10.7, 14.2, and 16.0% EE DDGS. In pigs fed 5.6% EE DDGS, however, C18:2 content in BF and belly fat were similar, but were

lower ($P < 0.05$) than jowl fat. The results for PUFA content followed a similar pattern as that for C18:2. A tendency ($P = 0.079$) for a dietary treatment × depot interaction was observed for the analysis of IV. Treatment groups shared the same mean separation patterns in each fat depot as that of C18:2 and PUFA (Figure 4.1). Among fat depots, jowl fat had greater ($P < 0.05$) IV than BF and belly fat regardless of dietary treatments. The IV of BF was greater ($P < 0.05$) than that of belly fat in pigs fed 16.0% EE DDGS, but no difference was observed in pigs fed 10.7, 5.6, and 14.2% EE DDGS.

In general, pigs fed 10.7, 5.6, and 14.2% EE DDGS sources had greater concentrations of SFA and MUFA, but lower PUFA content and IV compared with pigs fed 16.0% EE DDGS regardless of fat depot. These observations are explained mainly by the lower dietary lipid concentration of diets containing 10.7, 5.6, and 14.2% EE DDGS (4.94, 2.99, and 5.91% EE, respectively; Table 4.2) relative to diets containing 16.0% EE DDGS (6.58% EE). Graham et al. (2014b) also reported an increased IV of carcass fat depots when pigs were fed DDGS sources with greater oil content compared with pigs fed reduced-oil DDGS sources (9.6% oil DDGS vs. 5.4% oil DDGS in experiment 1, and 12.1% oil DDGS vs. 9.4% oil DDGS in experiment 2). Elevated dietary lipid intake is effective in depressing *de novo* synthesis of FA, which are usually more saturated, and leads to greater tissue deposition of FA from dietary lipids (Farnworth and Kramer, 1987; Chilliard, 1993). In the current study, the dietary lipids were primarily corn oil from DDGS or corn, which are high in unsaturated FA containing about 55% PUFA, 26% MUFA, and only 19% SFA (Table 4.1). Thus, reduced SFA *de novo* synthesis and increased unsaturated FA deposition resulted in a greater PUFA content and IV of carcass fat depots in pigs fed 16.0% EE DDGS compared with pigs fed the other dietary

treatments. Therefore, it can be speculated that the negative effect of feeding DDGS on pork fat quality may be reduced as more corn oil is extracted during DDGS production. However, although EE content of 5.6% EE DDGS was 5.1 and 8.6 percentage unit lower than the 10.7 and 14.2% EE DDGS sources, respectively, pigs fed these 3 DDGS sources generally had similar FA composition and IV in fat depots. It is possible that the oil content in 10.7 and 14.2% EE DDGS was less digestible and less utilized by pigs than that in other sources. Large variability in oil digestibility has been observed among DDGS sources. Kerr et al. (2013) reported that the apparent total tract digestibility of EE varied from 52.7 to 81.2% among 15 sources of DDGS.

Dietary treatment × fat depot interactions were observed for C18:2, PUFA, and IV. The magnitude of change in FA content, as a result of different amounts of dietary lipid intake, varied among the 3 fat depots. Backfat seemed more responsive to lipid content differences among dietary treatments than belly and jowl fat. For example, pigs fed 5.6% EE DDGS had a reduced ($P < 0.05$) C18:2 concentration in BF compared with that of pigs fed 14.2% EE DDGS, while there were no treatment differences between these 2 dietary treatments in jowl or belly fat. Moreover, pigs fed 5.6% EE DDGS had a lower dietary C18:2 intake (36.8 g/d) than pigs fed 16.0% EE DDGS (85.6 g/d), and consequently, had a reduced IV in 3 carcass fat depots; however, the magnitude of this reduction in IV was greater in BF (13.6 g/100g) compared with belly and jowl fat (11.0 and 9.7 g/100g, respectively; Figure 4.1). Some FA can be preferentially deposited in different tissues. A greater proportion of dietary C18:2 is deposited in BF compared with other carcass tissues (Kloareg et al., 2007). Therefore, C18:2 concentration of BF may be more sensitive to the changes in dietary C18:2 intake than belly and jowl fat. The C18:2

constitutes about 95% of the total PUFA content in pork fat, and predominantly determines IV of carcass fat depots. As a result, the dietary treatment × fat depot interactions observed for PUFA and IV greatly simulate that of C18:2.

Researchers have reported a greater IV of jowl fat than BF and belly fat (Evans et al., 2009; Duttlinger et al., 2012; Graham et al., 2014b), which is consistent with the observation in present study. Different rates of adipose tissue development can lead to variability in FA deposition among anatomical tissues (Lizardo et al., 2002). Late-developing tissues may deposit greater amount of SFA than early-developing tissues, because pigs have greater energy intake during the later stages of growth, and consequently, have more excess energy to support *de novo* synthesis of FA. According to the fat accretion patterns (from the distal ends of the body toward the visceral cavity) of food animals characterized by Hammond (1932), pigs deposit lipids earlier in jowl compared with loin and belly regions, which is in the agreement with the greater IV observed in jowl fat. In addition, the lower rate of FA *de novo* synthesis in jowl fat is also attributed to its lower activities of lipogenic enzymes compared with BF and belly fat during growing-finishing period (Mourot et al., 1995; Xu et al., 2010a).

Prediction of IV

Concentration of EE in the 7 sources of DDGS from the 2 experiments varied from 5.6 to 16.0%, similar to the range in oil content among sources of DDGS available in current markets. Consequently, IVP of the 8 dietary treatments increased from 24.4 to 83.5 g/100g, which resulted in a wide range of carcass fat IV (57.7 to 84.1 g/100g) in the combined dataset to test the selected prediction equations. Prediction error is a measurement of precision, and refers to the repeatability of an equation for different

observations, while prediction bias is a measurement of accuracy, and refers to the proximity of predicted estimates to the observed values. Among the equations to predict IV of BF from diet composition (Table 4.5), Eq. 8 resulted in the most accurate and precise IV estimates for BF because this equation demonstrated the lowest PE and bias. For the prediction of jowl fat IV (Table 4.6), Eq. 9 and 13 provided similar estimates, and had lower PE than the other equations for jowl fat, whereas Eq. 10 had the lowest prediction bias, but a slightly greater PE than Eq. 9 and 13. Among the equations for belly fat (Table 4.7), Eq. 14 and 16 had similar PE and bias, which were markedly lower than observed using Eq. 15. Finally, the prediction from Eq. 17 resulted in more precise and accurate estimates for the average IV of the 3 fat depots compared with Eq. 18 (Table 4.8).

Fatty acid composition of pork fat is a reflection of the FA composition of dietary lipid composition and intake (Averette Gatlin et al., 2002; Benz et al., 2011a). Therefore, the majority of the selected equations were developed based on the concentration and intake of dietary C18:2 (Eq. 4, 10, and 18), or IVP (Eq. 1, 2, 3, 6, 9, 11, 14, and 17), which is a composite value of unsaturation and quantity of dietary lipids in swine diets. However, using dietary C18:2 or IVP as a single predictor variable resulted in highly variable PE ranging from 3.43 to 8.36 g/100g, and bias ranging from -5.05 to 5.66 g/100g. In contrast, Eq. 8, 13, and 16 were developed from a meta-analysis by Paulk et al. (2015) and included multiple predictive factors involving diet fat composition, feeding days, NE content of diets, live performance criteria, and carcass composition. Therefore, it is reasonable to expect that adding these additional predictors may improve the prediction of IV because they more broadly account for the variation in dietary energy

concentration, as well as changes in diet composition that affect the intake and metabolic utilization of dietary lipid by pigs. Our results suggest that Eq. 8 increased the precision and accuracy of prediction for BF compared with equations using single predictors. However, limited improvement was observed when Eq. 13 and 16 were used to predict jowl and belly fat IV, respectively. In addition, previous researchers have reported a linear relationship between carcass fat IV and the percentage of DDGS inclusion in diets (Cromwell et al., 2011; Estrada, 2013). However, predictions using Eq. 5, 7, 12, and 15 had larger PE and bias than the other equations, regardless of fat depot. This was not surprising because the equations based on dietary inclusion rate of DDGS did not account for the variability in oil concentration among DDGS sources. However, directly relating the EE content of the 7 DDGS sources to the IV of BF using simple linear regression models resulted in a poor fit and was not significant (BF IV = 65.9 + 0.762 × EE% of DDGS, $R^2 = 0.42$, $P = 0.12$). Digestibility of oil content can vary from 52.7 to 81.2% among DDGS sources (Kerr et al., 2013), so it seems logical that the digestibility of dietary lipid should also be considered as a factor to accurately and precisely predict carcass fat IV of pigs fed high dietary levels of DDGS in future models.

In summary, reduced oil content of DDGS generally decreases the negative impact of feeding DDGS diets on pork fat quality by lowering the IV of pork fat depots. However, the magnitude of this improvement is not proportional to the amount of change in dietary lipid intake, and may be affected by the digestibility of oil in DDGS. Fatty acid composition varies among carcass fat depots, with jowl fat having greater IV than BF and belly fat, but BF appears to be more sensitive to the changes in dietary lipid content. The use of published carcass fat IV prediction equations results in variable precision and

accuracy in estimating IV of carcass fat depots. In general, including additional factors such as dietary energy content, growth performance, and carcass composition measures, appears to provide better IV predictions than those that are only based on the characteristics and quantities of dietary lipids. Using the percentage of DDGS in diet as a predictor of carcass fat depot IV, results in the poorest prediction.

Table 4.1. Fatty acid analysis of distillers dried grains with solubles (DDGS) with variable ether extract (EE) content (as-fed basis)

Item	10.7% EE DDGS	5.6% EE DDGS	14.2% EE DDGS	16.0% EE DDGS
EE, %	10.70	5.61	14.19	15.98
Fatty acids[1], % of EE				
C14:0	0.13	0.10	0.07	0.10
C16:0	15.70	15.59	15.34	14.63
C16:1	0.20	0.23	0.13	0.14
C17:0	0.07	0.07	0.08	0.08
C18:0	2.19	2.58	2.15	2.05
C18:1	24.27	25.75	24.61	25.62
C18:2	53.53	51.76	53.92	53.87
C18:3	1.80	1.74	1.63	1.61
C20:0	0.48	0.47	0.49	0.43
C20:1	0.37	0.35	0.36	0.34
C22:0	0.24	0.32	0.29	0.27
C24:0	0.32	0.37	0.29	0.28
SFA[2]	19.11	19.47	18.70	17.83
MUFA[3]	24.84	26.33	25.10	26.10
PUFA[4]	55.32	53.50	55.55	55.47
IV[5], g/100g	119	117	119	120
IVP[6]	127	66	169	192

[1] Fatty acids: myristic (C14:0), palmitic (C16:0), palmitoleic (C16:1), margaric (C17:0), stearic (C18:0), oleic (C18:1), linoleic (C18:2), linolenic (C18:3), arachidic (C20:0), gadoleic (C20:1), behenoic (C22:0), and lignoceric (C24:0).

[2] Total saturated fatty acids=([C8:0] + [C10:0] + [C12:0] + [C14:0] + [C16:0] + [C17:0] + [C18:0] + [C20:0] + [C22:0] + [C24:0]); brackets indicate concentration.

[3] Total monounsaturated fatty acids = ([C14:1] + [C16:1] + [C18:1 – 9c] + [C18:1 – 11c] + [C20:1] + [C24:1]); brackets indicate concentration.

[4] Total polyunsaturated fatty acids = ([C18:2*n*-6] + [C18:3*n*-3] + [C18:3*n*-6] + [C20:2] + [C20:4*n*-6]); brackets indicate concentration.

[5] Calculated iodine value = [C16:1] × 0.95 + [C18:1] × 0.86 + [C18:2] × 1.732 + [C18:3] × 2.616 + [C20:1] × 0.785 + [C22:1] × 0.723; brackets indicate concentration (AOCS, 1998).

[6] Iodine value product = IV × % ether extract × 0.10 (Madsen et al., 1992).

Table 4.2. Fatty acid analysis of diets (as-fed basis)

Item	10.7% EE DDGS[1]	5.6% EE DDGS[1]	14.2% EE DDGS[1]	16.0% EE DDGS[1]	Holding[2]
EE, %	4.94	2.99	5.91	6.58	2.14
Fatty acids[3], % of EE					
C14:0	0.12	0.08	0.07	0.05	0.11
C16:0	15.19	15.05	14.80	14.43	14.58
C16:1	0.19	0.19	0.15	0.17	0.10
C17:0	0.11	0.10	0.08	0.08	0.10
C18:0	2.38	2.62	2.09	2.14	2.44
C18:1	24.49	25.19	24.48	25.26	22.94
C18:2	52.90	52.14	54.29	53.95	51.41
C18:3	2.25	2.38	2.21	2.06	3.11
C20:0	0.46	0.44	0.37	0.39	0.59
C20:1	0.35	0.37	0.32	0.29	0.42
C22:0	0.28	0.30	0.23	0.24	0.27
C24:0	0.34	0.34	0.23	0.25	0.35
SFA[4]	18.88	18.93	17.89	17.57	18.44
MUFA[5]	25.03	25.75	24.95	25.72	23.46
PUFA[6]	55.15	54.52	56.50	56.01	54.52
IV[7], g/100g	119	119	121	121	117
IVP[8]	59	35	72	80	25

[1] Diets containing 40% DDGS from different sources with 10.7, 5.6, 14.2, or 16.0% ether extract (EE; as-fed) content. Values are presented as the average among 4 phases and weighted for total feed consumption in each phase.

[2] Corn-soybean meal diet with no addition of DDGS that was fed to pigs 5 days prior to slaughter due to depletion of DDGS.

[3] Fatty acids: myristic (C14:0), palmitic (C16:0), palmitoleic (C16:1), margaric (C17:0), stearic (C18:0), oleic (C18:1), linoleic (C18:2), linolenic (C18:3), arachidic (C20:0), gadoleic (C20:1), Behenoic (C22:0), and Lignoceric (C24:0).

[4] Total saturated fatty acids=([C8:0] + [C10:0] + [C12:0] + [C14:0] + [C16:0] + [C17:0] + [C18:0] + [C20:0] + [C22:0] + [C24:0]); brackets indicate concentration.

[5] Total monounsaturated fatty acids = ([C14:1] + [C16:1] + [C18:1 – 9c] + [C18:1 – 11c] + [C20:1] + [C24:1]); brackets indicate concentration.

[6] Total polyunsaturated fatty acids = ([C18:2*n*-6] + [C18:3*n*-3] + [C18:3*n*-6] + [C20:2] + [C20:4*n*-6]); brackets indicate concentration.

[7] Calculated iodine value = [C16:1] × 0.95 + [C18:1] × 0.86 + [C18:2] × 1.732 + [C18:3] × 2.616 + [C20:1] × 0.785 + [C22:1] × 0.723; brackets indicate concentration (AOCS, 1998).

[8] Iodine value product = IV × % ether extract × 0.10 (Madsen et al., 1992)

Table 4.3. Selected prediction equations for iodine value (IV) of carcass backfat, jowl fat, belly fat, and the average of 3 fat depots

Item	Reference	Equation	R^2
Backfat			
Eq. 1	Madsen et al., 1992	47.1 + 0.14 × IVP[1] intake/d	0.86
Eq. 2	Boyd et al., 1997	52.4 + 0.315 × Diet IVP	-
Eq. 3	Benz et al., 2011a	51.946 + 0.2715 × Diet IVP	0.16
Eq. 4	Benz et al., 2011a	35.458 + 14.324 × Diet C18:2, %	0.73
Eq. 5	Cromwell et al., 2011	64.5 + 0.432 × DDGS in diet, %	0.92
Eq. 6	Estrada, 2013	60.13 + 0.27 × Diet IVP	0.81
Eq. 7	Estrada, 2013	70.06 + 0.29 × DDGS in diet, %	0.81
Eq. 8	Paulk et al., 2015[2]	84.83 + (6.87 × I EFA) - (3.90 × F EFA) - (0.12 × I d) - (1.30 × F d) - (0.11 × I EFA × F d) + (0.048 × F EFA × I d) + (0.12 × F EFA × F d) - (0.0060 × F NE) + (0.0005 × F NE × F d) - (0.26 × BF)	0.95
Jowl fat			
Eq. 9	Benz et al., 2011a	56.479 + 0.247 × Diet IVP	0.32
Eq. 10	Benz et al., 2011a	47.469 + 10.111 × Diet C18:2,%	0.90
Eq. 11	Estrada, 2013	64.54 + 0.27 × Diet IVP	0.81
Eq. 12	Estrada, 2013	72.99 + 0.24 × DDGS in diet, %	0.81
Eq. 13	Paulk et al., 2015[2]	85.50 + (1.08 × I EFA) + (0.87 × F EFA) - (0.014 × I d) - (0.050 × F d) + (0.038 × I EFA × I d) + (0.054 × F EFA × F d) - (0.0066 × I NE) + (0.071× I BW) - (2.19 × ADFI) - (0.29 × BF)	0.93
Belly fat			
Eq. 14	Estrada, 2013	58.32 + 0.25 × Diet IVP	0.74
Eq. 15	Estrada, 2013	67.35 + 0.26 × DDGS in diet, %	0.75
Eq. 16	Paulk et al., 2015[2]	106.16 + (6.21 × I EFA) - (1.50 × F d) - (0.11 × I EFA × F d) - (0.012 × I NE) + (0.00069 × I NE × F d) - (0.18 × HCW) - (0.25 × BF)	0.94
Average of 3 depots			
Eq. 17	Kellner, 2014	58.102 + 0.2149 × Diet IVP	0.93
Eq. 18	Kellner, 2014	58.566 + 0.1393 × C18:2 intake/d, g	0.94

[1] Iodine value product = dietary IV × % dietary lipids × 0.10 (Madsen et al., 1992).

[2] I = initial diet, F = final diet, d = days of diet fed, EFA = essential fatty acids (C18:2 and C18:3; %), NE = net energy (kcal/kg), BW = body weight (kg), ADFI = overall average daily feed intake (kg), HCW = hot carcass weight (kg), and BF = backfat depth (mm).

Table 4.4. Effects of dietary distillers dried grains with solubles (DDGS) and fat depots on the fatty acid profile of carcass backfat, jowl fat, and belly fat samples

	10.7% EE DDGS[1]			5.6% EE DDGS[1]			14.2% EE DDGS[1]			16.0% EE DDGS[1]			Pooled	*P*-values		
Item[2]	Back	Belly	Jowl	Back	Belly	Jowl	Back	Belly	Jowl	Back	Belly	Jowl	SEM	Diet	Depot	Diet× depot
C14:0	1.24^{b}	1.40^{d}	1.27^{b}	1.25^{b}	1.43^{d}	1.28^{bc}	1.21^{b}	1.35^{c}	1.21^{b}	1.04^{a}	1.23^{b}	1.09^{a}	0.03	<0.01	<0.01	0.91
C16:0	22.84^{d}	23.37^{d}	21.12^{c}	23.44^{d}	23.55^{d}	21.28^{c}	22.91^{d}	23.20^{d}	20.78^{bc}	20.25^{b}	20.88^{c}	18.95^{a}	0.26	<0.01	<0.01	0.53
C16:1	2.05^{cd}	2.64^{g}	2.57^{fg}	1.92^{bc}	2.48^{efg}	2.46^{ef}	1.87^{b}	2.48^{fg}	2.32^{e}	1.57^{a}	2.12^{d}	2.09^{cd}	0.06	<0.01	<0.01	0.91
C17:0	0.41^{defg}	0.39^{cdef}	0.45^{g}	0.37^{bcde}	0.37^{bcd}	0.42^{fg}	0.39^{def}	0.35^{abc}	0.42^{efg}	0.34^{abc}	0.31^{a}	0.33^{ab}	0.02	<0.01	<0.01	0.32
C17:1	0.37^{cd}	0.36^{cd}	0.46^{f}	0.32^{b}	0.34^{bc}	0.42^{e}	0.32^{b}	0.32^{b}	0.40^{de}	0.26^{a}	0.27^{a}	0.33^{bc}	0.01	<0.01	<0.01	0.74
C18:0	11.16^{ef}	10.43^{d}	8.41^{b}	11.97^{g}	10.58^{de}	8.75^{bc}	11.36^{fg}	10.16^{d}	8.54^{bc}	9.17^{c}	8.58^{bc}	6.95^{a}	0.25	<0.01	<0.01	0.36
C18:1	38.46^{cd}	39.88^{ef}	40.84^{f}	38.12^{c}	39.22^{de}	40.43^{f}	37.45^{bc}	39.97^{ef}	40.06^{ef}	34.98^{a}	36.67^{b}	38.17^{cd}	0.40	<0.01	<0.01	0.31
C18:2	18.86^{bc}	17.09^{a}	19.80^{cd}	18.21^{ab}	17.60^{ab}	19.85^{cd}	20.01^{cd}	17.67^{ab}	21.08^{d}	27.60^{f}	25.19^{e}	26.56^{f}	0.53	<0.01	<0.01	0.04
C18:3	0.68^{a}	0.65^{a}	0.80^{c}	0.63^{a}	0.66^{a}	0.79^{bc}	0.68^{ab}	0.64^{a}	0.80^{cd}	0.86^{d}	0.84^{cd}	0.91^{e}	0.02	<0.01	<0.01	0.04
C20:0	0.27^{cd}	0.22^{ab}	0.22^{ab}	0.28^{d}	0.24^{ab}	0.23^{ab}	0.26^{cd}	0.23^{ab}	0.22^{ab}	0.24^{bc}	0.22^{ab}	0.22^{a}	0.01	0.19	<0.01	0.57
C20:1	0.87^{cd}	0.76^{b}	0.90^{d}	0.86^{cd}	0.76^{b}	0.90^{d}	0.84^{c}	0.77^{b}	0.88^{cd}	0.76^{b}	0.70^{a}	0.85^{cd}	0.02	<0.01	<0.01	0.41
C20:4	0.38^{ab}	0.41^{bc}	0.46^{de}	0.37^{a}	0.42^{c}	0.48^{e}	0.38^{ab}	0.41^{bc}	0.46^{de}	0.44^{cd}	0.49^{ef}	0.51^{f}	0.01	<0.01	<0.01	0.42
SFA[3]	36.12^{c}	36.00^{c}	31.70^{b}	37.54^{d}	36.39^{c}	32.20^{b}	36.33^{cd}	35.48^{c}	31.41^{b}	31.26^{b}	31.45^{b}	27.79^{a}	0.46	<0.01	<0.01	0.36
MUFA[4]	42.09^{cd}	44.01^{ef}	45.12^{f}	41.56^{c}	43.17^{de}	44.58^{f}	40.83^{bc}	43.97^{ef}	44.10^{ef}	37.89^{a}	40.11^{b}	41.87^{c}	0.46	<0.01	<0.01	0.34
PUFA[5]	19.91^{bc}	18.17^{a}	21.06^{cd}	19.21^{ab}	18.68^{ab}	21.12^{cd}	21.08^{cd}	18.68^{ab}	22.35^{d}	28.90^{f}	26.52^{e}	27.99^{f}	0.56	<0.01	<0.01	0.04
IV[6]	70.33^{ab}	68.96^{a}	74.84^{c}	68.64^{a}	69.08^{a}	74.42^{c}	71.28^{b}	69.88^{ab}	76.21^{c}	82.28^{e}	80.07^{d}	84.09^{f}	0.78	<0.01	<0.01	0.08

[1] Diets containing 40% DDGS from different sources with 10.7, 5.6, 14.2, or 16.0% ether extract (EE; as-fed) content.

[2] Concentrations of fatty acids are expressed as grams of fatty acid/100g fat. Fatty acids: myristic (C14:0), palmitic (C16:0), palmitoleic (C16:1), margaric (C17:0), heptadecenoic (C17:1), stearic (C18:0), oleic (C18:1), linoleic (C18:2), linolenic (C18:3), arachidic (C20:0), gadoleic (C20:1), arachidonic (C20:4).

[3] Total saturated fatty acids=([C8:0] + [C10:0] + [C12:0] + [C14:0] + [C16:0] + [C17:0] + [C18:0] +[C20:0] + [C22:0] + [C24:0]); brackets indicate concentration.

[4] Total monounsaturated fatty acids = ([C14:1] + [C16:1] + [C18:1 – 9c] + [C18:1 – 11c] + [C20:1] + [C24:1]); brackets indicate concentration.

[5] Total polyunsaturated fatty acids = ([C18:2*n*-6] + [C18:3*n*-3] + [C18:3*n*-6] + [C20:2] + [C20:4*n*-6]); brackets indicate concentration.

[6] Calculated iodine value = [C16:1] × 0.95 + [C18:1] × 0.86 + [C18:2] × 1.732 + [C18:3] × 2.616 + [C20:1] × 0.785 + [C22:1] × 0.723; brackets indicate concentration (AOCS, 1998).

[a-g] Means with different superscripts within a row differ ($P < 0.05$).

Table 4.5. Comparison of prediction equations for backfat iodine value (IV; g/100g)

Item	Present experiment				Chapter 2[1]				PE[3]	Bias
	10.7% EE DDGS[2]	5.6% EE DDGS[2]	14.2% EE DDGS[2]	16.0% EE DDGS[2]	CON	LOW	MED	HIGH		
Observed IV	70.33	68.64	71.28	82.28	57.72	74.11	74.35	78.96	-	-
Predicted IV[4]										
Eq. 1	68.28	60.51	71.87	74.37	56.37	62.46	66.76	77.48	6.43	-4.95
Eq. 2	70.92	63.55	74.97	77.46	60.07	65.43	69.33	78.71	4.60	-2.15
Eq. 3	67.91	61.56	71.40	73.55	58.56	63.18	66.54	74.62	6.45	-5.05
Eq. 4	72.88	57.75	81.40	86.27	51.01	61.56	69.68	88.49	8.36	-1.08
Eq. 5	81.42	81.42	81.42	81.42	64.50	81.42	81.42	81.42	8.26	7.10
Eq. 6	76.00	69.69	79.47	81.61	66.71	71.30	74.64	82.68	5.04	3.05
Eq. 7	81.66	81.66	81.66	81.66	70.06	81.66	81.66	81.66	9.19	8.00
Eq. 8	71.16	64.28	74.96	76.99	62.35	68.16	71.90	81.14	4.01	-0.84

[1] Previous experiment that was conducted in the same facility with the same genetic line of pigs, and followed the same experimental procedures with the present experiment. CON = corn-soybean meal control diet; LOW = 40% low-oil (5.9%) DDGS diet; MED = 40% medium-oil (9.9%) DDGS diet; and HIGH = 40% high-oil (14.2%) DDGS diet.

[2] Diets containing 40% DDGS from different sources with 10.7, 5.6, 14.2, or 16.0% ether extract (EE; as-fed) content.

[3] Prediction error.

[4] Prediction equations are presented in Table 4.3.

Table 4.6. Comparison of prediction equations for jowl fat iodine value (IV; g/100g)

Item	Present experiment				Chapter 2[1]				PE[3]	Bias
	10.7% EE DDGS[2]	5.6% EE DDGS[2]	14.2% EE DDGS[2]	16.0% EE DDGS[2]	CON	LOW	MED	HIGH		
Observed IV	74.84	74.42	76.21	84.09	62.20	71.22	72.25	76.89	-	-
Predicted IV[4]										
Eq. 9	71.00	65.22	74.18	76.13	62.49	66.70	69.75	77.11	4.92	-3.69
Eq. 10	73.89	63.20	79.90	83.34	58.44	65.89	71.63	84.91	5.57	-1.37
Eq. 11	80.41	74.10	83.88	86.02	71.12	75.71	79.05	87.09	6.55	5.66
Eq. 12	82.59	82.59	82.59	82.59	72.99	82.59	82.59	82.59	8.33	7.38
Eq. 13	70.94	66.96	73.20	74.97	64.04	68.19	70.48	76.36	4.73	-3.37

[1] Previous experiment that was conducted in the same facility with the same genetic line of pigs, and followed the same experimental procedures with the present experiment. CON = corn-soybean meal control diet; LOW = 40% low-oil (5.9%) DDGS diet; MED = 40% medium-oil (9.9%) DDGS diet; and HIGH = 40% high-oil (14.2%) DDGS diet.

[2] Diets containing 40% DDGS from different sources with 10.7, 5.6, 14.2, or 16.0% ether extract (EE; as-fed) content.

[3] Prediction error.

[4] Prediction equations are presented in Table 4.3.

Table 4.7. Comparison of prediction equations for belly fat iodine value (IV; g/100g)

Item	Present experiment				Chapter 2[1]				PE[3]	Bias
	10.7% EE DDGS[2]	5.6% EE DDGS[2]	14.2% EE DDGS[2]	16.0% EE DDGS[2]	CON	LOW	MED	HIGH		
Observed IV	68.96	69.08	69.88	80.07	60.17	70.74	72.03	76.41	-	-
Predicted IV[4]										
Eq. 14	73.02	67.17	76.23	78.21	64.41	68.66	71.76	79.20	3.43	1.41
Eq. 15	77.75	77.75	77.75	77.75	67.35	77.75	77.75	77.75	6.66	5.53
Eq. 16	73.54	69.24	76.11	78.49	62.51	69.06	71.91	80.29	3.27	1.73

[1] Previous experiment that was conducted in the same facility with the same genetic line of pigs, and followed the same experimental procedures with the present experiment. CON = corn-soybean meal control diet; LOW = 40% low-oil (5.9%) DDGS diet; MED = 40% medium-oil (9.9%) DDGS diet; and HIGH = 40% high-oil (14.2%) DDGS diet.

[2] Diets containing 40% DDGS from different sources with 10.7, 5.6, 14.2, or 16.0% ether extract (EE; as-fed) content.

[3] Prediction error.

[4] Prediction equations are presented in Table 4.3.

Table 4.8. Comparison of prediction equations for the average iodine value (IV; g/100g) of backfat, jowl fat, and belly fat

Item	Present experiment				Chapter 2[1]					
	10.7% EE DDGS[2]	5.6% EE DDGS[2]	14.2% EE DDGS[2]	16.0% EE DDGS[2]	CON	LOW	MED	HIGH	PE[3]	Bias
Observed IV	71.38	70.71	72.46	82.15	60.03	72.02	72.88	77.42	-	-
Predicted IV[4]										
Eq. 17	70.74	65.71	73.50	75.20	63.34	66.99	69.65	76.05	3.93	-2.23
Eq. 18	67.93	64.43	69.60	70.67	62.68	65.30	67.26	71.97	6.17	-4.90

[1] Previous experiment that was conducted in the same facility with the same genetic line of pigs, and followed the same experimental procedures with the present experiment. CON = corn-soybean meal control diet; LOW = 40% low-oil (5.9%) DDGS diet; MED = 40% medium-oil (9.9%) DDGS diet; and HIGH = 40% high-oil (14.2%) DDGS diet.

[2] Diets containing 40% DDGS from different sources with 10.7, 5.6, 14.2, or 16.0% ether extract (EE; as-fed) content.

[3] Prediction error.

[4] Prediction equations are presented in Table 4.3.

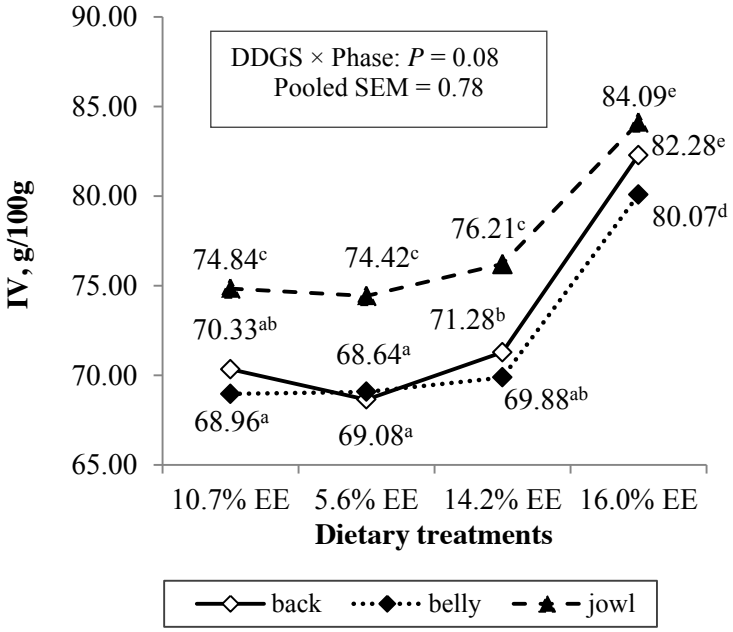

Figure 4.1. Effects of dietary dried distillers grains with solubles (DDGS) with variable ether extract (EE) content on iodine value (IV) of backfat, belly, and jowl fat. Treatments include diets containing 40% DDGS from different sources with 10.7, 5.6, 14.2, or 16.0% EE content. [a-e] Means with different superscripts differ ($P < 0.05$).

CHAPTER 5

Effects of feeding diets containing distillers dried grains with solubles and wheat middlings with equal predicted dietary NE on growth performance and carcass composition of growing-finishing pigs

Summary

Distillers dried grains with solubles (DDGS) and wheat middlings (WM) have been increasingly used in U.S. swine diets to decrease feed cost. However, the caloric and nutrient utilization efficiency when feeding diets containing these high-fiber ingredients needs to be improved by using the NE system for diet formulation. This experiment evaluated the effects of feeding DDGS and WM with similar estimated dietary NE content on growth performance and carcass characteristics of growing-finishing pigs. Pigs (n = 384; initial BW = 29.1 ± 3.6 kg) were blocked by initial BW, and within blocks, pens were allotted randomly to 1 of 4 dietary treatments (9 pigs/pen, 12 replicates/treatment) in a 4-phase feeding program (29 to 50 kg, 50 to 75 kg, 75 to 100 kg, and 100 to 120 kg BW). Dietary treatments were arranged in a 2 × 2 factorial design and formulated to consist of: 1) corn and soybean meal, 2) CON with 30% DDGS, 3) CON with 15% WM, and 4) CON with 30% DDGS and 15% WM. Soybean oil was added to all diets except CON, to maintain similar dietary NE content within phases. Net energy values of 2,672, 2,087, 2,114, 2,113, and 7,545 kcal/kg (as-fed) were used for corn, soybean meal, DDGS, WM, and soybean oil, respectively. Diets met or exceeded nutrient requirements and were formulated to contain the same concentrations of standardized ileal digestible Lys within phases. No significant interactions for DDGS × WM × phase or DDGS × WM were observed for all growth performance criteria. Feeding 30% DDGS diets decreased ($P < 0.05$) ADFI (1.76 vs. 1.86 kg/d) and ADG (0.85 vs. 0.91 kg/d) in

phase 1, but not in other phases. Gain:feed of pigs fed diets containing DDGS was not different during phase 1 to 3, but was greater ($P < 0.01$) in phase 4 (0.313 vs. 0.291), compared with that of pigs fed diets with no addition of DDGS. Feeding 15% WM did not affect ADFI or G:F, but reduced ($P < 0.05$) ADG in phase 1 (0.86 vs. 0.90 kg/d) but not in phase 2 to 4. No DDGS × WM interaction was observed for carcass traits. Pigs fed diets containing 30% DDGS had reduced ($P < 0.01$) HCW (86.5 vs. 89.9 kg), carcass yield (72.3 vs. 73.6%), LM area (45.0 vs. 47.9 cm^2), and percent fat free lean (52.1 vs. 53.4%), but backfat depth was not affected compared with pigs fed diets without DDGS. Adding 15% WM to diets reduced carcass yield (72.7 vs. 73.1%; $P < 0.05$) and HCW (87.7 vs. 88.7 kg; $P < 0.10$), but other carcass traits were not affected. In conclusion, feeding diets containing 30% DDGS or 15% WM reduced pig growth performance particularly in early growing phase, and feeding diets containing 30% DDGS had a greater negative impact on carcass characteristics than when pigs were fed diets containing 15% WM. Overall ADG and G:F were not affected by feeding 30% DDGS or 15% WM when diets were formulated on the NE basis, but more accurate and dynamic estimation of NE content for DDGS sources is needed to optimize caloric efficiency at different physiological ages of pigs.

Key words: carcass characteristics, distillers dried grains with solubles, wheat middlings, growing-finishing pigs, growth performance

Introduction

High prices of traditional feed ingredients (i.e. corn and soybean meal) results in increased demand for alternative, high-fiber ingredients such as distillers dried grains with solubles (**DDGS**) and wheat middlings (**WM**) in swine diets. Corn DDGS is a co-

product of ethanol production, and is a good source of energy, digestible AA, and digestible P for growing-finishing pigs. However, DDGS sources typically contain less NE than corn (NRC, 2012). Researchers (Graham et al., 2014b; Wu, chapter 3) have shown that NE content may be further reduced due to the majority of U.S. ethanol plants using oil extraction technology to produce reduced-oil DDGS. Wheat middlings is a co-product of the flour milling industry and consists of fine particles of wheat bran, wheat shorts, wheat germ, wheat flour, and the "tail of the milling" (Erickson et al., 1985). Similar to DDGS, WM has greater concentrations of CP and NDF, but less NE content compared with corn.

Reductions in growth performance, HCW, and carcass yield have been reported when adding corn DDGS and (or) WM to growing-finishing diets (Asmus et al., 2011; Salyer et al., 2012). However, these negative responses may be the result of formulating diets using the ME system, which often overestimates energy value of high-fiber and high-protein ingredients like DDGS and WM (Noblet and van Milgen, 2004). In contrast, NE system should provide better estimates of the energy requirements of pigs and energy value of feed ingredients than the ME system because NE accounts for the energy cost of metabolic utilization of nutrients and physical activities of pigs (Noblet and van Milgen, 2004). Therefore, the objective of this study was to determine the effects of feeding DDGS and WM on the growth performance and carcass characteristics of growing-finishing pigs when diets were formulated on a NE basis.

Materials and methods

All experimental procedures in this study were approved by the University of Minnesota Institutional Animal Care and Use Committee (St. Paul, MN).

Animals and housing

Barrows (n = 384) were blocked by initial BW (29.1 ± 3.6 kg) and allotted to 12 blocks (4 pens/block; 8 pigs/pen). Pigs were housed in an environmentally controlled grower-finisher facility at the University of Minnesota West Central Research and Outreach Center (Morris, MN). Each pen (1.60 × 4.5 m) consisted of completely slatted, concrete floors and was equipped with a nipple waterer and 1 single-sided self-feeder with 4 eating spaces. Room temperature of the facility was maintained at about 20°C. Pigs were allowed ad libitum access to feed and water throughout the experiment. Pigs that showed signs of poor health were treated individually with appropriate medication or removed from the experiment.

Diets and experimental design

One lot of DDGS (POET LLC, Mitchell, SD) and 1 lot of WM (Gavilon LLC, Omaha, NE) were obtained for the entire experiment. Upon arrival, samples were collected from each lot for chemical analyses (Table 5.1). Corn and soybean meal were obtained in multiple lots from the same source. Analyzed nutrient composition of samples collected from the first lot was used to formulate diets throughout the experiment. Pens of pigs were allotted randomly to 1 of 4 dietary treatments (Table 5.2 and 5.3) in a 4-phase feeding program (29 to 50 kg, 50 to 75 kg, 75 to 100 kg, and 100 to 120 kg BW for phases 1 to 4, respectively). Phases were switched when average BW of pigs in each pen reached the target starting BW ± 2.3 kg of the subsequent phase. Dietary treatments consisted of: 1) corn-soybean meal (**CON**), 2) CON with 30% DDGS, 3) CON with 15% WM, and 4) CON with 30% DDGS and 15% WM. Soybean oil was added to the diets containing DDGS and WM to match the dietary NE of CON diet within each phase. Estimated NE

value of DDGS (2,114 kcal/kg as-fed) was obtained using a prediction equation [NE, kcal/kg = -1,130 + (0.727 × GE) – (10.829 × NDF) + (23.861 × ether extract); DM basis] developed from unpublished data from University of Minnesota. Recommended NE values (kcal/kg as-fed) from NRC (2012) were used for corn (2,672), soybean meal (2,087), WM (2,113), and soybean oil (7,545). Diets were balanced for standardized ileal digestible (**SID**) AA and standardized total tract digestible (**STTD**) P, and were calculated to contain the same SID Lys:NE across diets within phases. Coefficients of AA digestibility for DDGS sources were obtained from equations reported by Almeida et al. (2013) based on analyzed AA composition. Coefficients for SID AA and STTD P for WM, corn, and soybean meal, as well as the coefficient for STTD P of DDGS, were obtained from NRC (2012). All diets met or exceeded the nutrient requirements of growing-finishing pigs predicted by the NRC (2012) model. Prediction of nutrient requirements was based on inputs of growth performance (initial BW = 39 kg; final BW = 123 kg; overall ADFI = 2.72 kg/d) and lean growth rate (142 g/d) of pigs fed corn-soybean meal diets in a similar experiment (chapter 2) conducted in the same facilities with the same genetic line of pigs. Body weight of individual pigs and feed disappearance in each pen were measured every other week to calculate ADG, ADFI, and G:F. Feed samples were obtained and frozen (-20°C) when each batch of feed was mixed, and 4 samples of each treatment (1 sample from each of the 4 phases; 16 samples total) were selected randomly for analysis of nutrient composition.

Carcass measurements

When the average BW of pigs reached 120 kg, backfat (**BF**) depth and LM area (**LMA**) were measured between the 10th and 11th ribs using an ALOKA 500V real-time

ultrasound machine (Corometrics Medical Systems, Wallingford, CT) by a certified technician. Pigs were divided into 2 groups (pigs from blocks 1 to 6 with the greatest initial BW were in group 1, and pigs from blocks 7 to 12 with the lowest initial BW were in group 2) and harvested at 2 separate times that were 7 d apart. For each harvest group, after ultrasound measurements were obtained, final BW was determined and pigs were tattooed individually and transported to a commercial abattoir (Hormel Foods; Austin, MN). Hot carcass weight was recorded at harvest and was used to calculate carcass yield using: carcass yield, % = HCW/Final BW × 100. Percentage of carcass fat free lean (**FFL%**) was calculated using: FFL% = {[2.620 + (0.456 × sex of pig) – (3.358 × 10th rib backfat depth, cm) + (0.306 × 10th rib LMA, cm^2) + (0.401 × HCW, kg)]/HCW, kg} × 100, where sex of pig is defined as barrow = 1 and gilt = 2 (NPPC, 2000).

Chemical analysis

One sample of each of DDGS, WM, corn, and soybean meal and 16 samples of complete diets were analyzed for nutrient composition at the Agricultural Experiment Station Chemical Laboratory (Columbia, MO). Standard procedures from AOAC (2006) were followed for analysis of moisture (Method 934.01), CP (Method 990.03), ether extract (**EE**; Method 920.39), ADF (Method 973.18), NDF (Holst, 1973), Ca and P (Method 985.01), complete AA profile [Method 982.30 E (a, b, c)], and starch (AACC, Approved Methods, No. 76-13). Bulk densities of 16 samples of complete diets were analyzed in triplicate at the University of Minnesota Swine Nutrition Laboratory (Table 5.4).

Statistical analysis

All statistical analyses were conducted using the MIXED procedure (SAS Inst. Inc., Cary, NC) with a 2 × 2 factorial arrangement of treatments within a randomized complete block design. Pen served as the experimental unit for all data analyses. Growth performance data of each phase were analyzed using a statistical model that included fixed effects of DDGS × WM × phase, DDGS × WM, DDGS × phase, WM × phase, DDGS, and WM (full model), with block as a random effect and repeated measures for phases. For analysis of ADFI, ADG, and G:F, the full statistical model was simplified by removing DDGS × WM × phase interaction if it was not significant ($P > 0.10$), and the degrees of freedom of non-significant interactions were pooled to test the remaining fixed effects. Body weights were analyzed using the full model. For analysis of carcass characteristics, the statistical model included fixed effects of DDGS × WM, DDGS, and WM, with block as a random effect. Final BW was used as a covariate for BF depth, LMA, and FFL% if the effect of the covariate was significant ($P < 0.05$). Means are reported as least-squares means and were separated by the PDIFF option with a Tukey-Kramer adjustment. The significance level was set at $P < 0.05$, and trends are reported when $0.05 < P < 0.10$.

Results and discussion

Growth performance

During the feeding period, 11 pigs (3, 4, 2, and 2 pigs from CON, 30% DDGS, 15% WM, and 30% DDGS + 15% WM treatments, respectively) were removed from the study due to poor health or death.

Numerous studies have been conducted to evaluate the effects of feeding DDGS and WM on growth performance of growing-finishing pigs. Stein and Shurson (2009) reviewed more than 23 published studies and suggested that acceptable growth performance was maintained in most, but not all, experiments where up to 30% DDGS was added to diets. In contrast, feeding diets containing as little as 10% WM often resulted in decreased ADG and G:F in growing-finishing pigs (Feoli et al., 2006; Asmus et al., 2011; Salyer et al., 2012). However, these reported reductions in growth performance are likely due to using the ME system when formulating DDGS and WM diets. The ME system does not account for energy losses from heat increment and consequently, tends to overestimate the available energy content of high-fiber feed ingredients (Noblet and van Milgen, 2004). Therefore, we hypothesized that using the NE system, which better represents the actual feed energy value and energy requirements of pigs, as the basis for diet formulation will reduce some of the negative effects observed in previous studies when adding DDGS and WM to growing-finishing diets.

In the present study, the interaction of DDGS × WM × phase was not significant for ADFI, ADG, and G:F, and therefore, was removed from the statistical model (Table 5.5). In the simplified model, there was no significant DDGS × WM interaction for ADFI. Overall ADFI of pigs fed CON was greater ($P < 0.05$) than that of pigs fed 30% DDGS + 15% WM treatment, but was not different from those fed 30% DDGS or 15% WM treatments (Table 5.6). No treatment differences in overall ADFI were observed among pigs fed 15% WM diets, 30% DDGS diets, and 30% DDGS + 15% WM diets. A significant interaction ($P < 0.05$) of DDGS × phase was observed, indicating that the effect of 30% dietary DDGS on ADFI varied over the feeding phases. In particular,

feeding 30% DDGS decreased ($P < 0.05$) ADFI in phase 1, but not in phases 2 to 4, compared with feeding diets without addition of DDGS (Figure 5.1). This observation was consistent with previous experiments that reported a decrease in ADFI of pigs fed 40% DDGS in early feeding phases compared with pigs fed corn-soybean meal control diets (Hardman, 2013; Wu, chapter 2). One possible reason for this observation is that increased bulkiness of dietary fiber in diets containing DDGS may limit the physical gut capacity of pigs, preventing them from achieving sufficient energy intake. In addition, the ability of pigs to maintain feed intake when consuming fiber-rich diets is related to the physiological age of pigs (Kennelly and Aherne, 1980), which may explain the unaffected ADFI observed for pigs fed diets containing DDGS in phases 2 to 4. The concentration of NDF in DDGS is about 3 times greater than in corn (Xu et al., 2010a), resulting in increased dietary NDF concentration when DDGS is added to diets. As a consequence, the 30% DDGS diet and 30% DDGS + 15% WM diets fed in phase 1 had decreased bulk densities compared with that of CON diet (Table 5.4). Based on bulk density and ADFI in phase 1, pigs had an average volume of feed intake (L/day) of 3.16 CON diet, 3.69 15% WM diet, 3.21 liter of 30% DDGS diet, and 3.27 liter of 30% DDGS + 15% WM diet. It appeared that pigs fed DDGS did not maintain similar volume of feed intake compared with pigs fed WM, even though bulk density of diets containing DDGS was greater than that of diets containing WM. Therefore, the "gut fill" effect can only partially explain the reduced ADFI of pigs fed DDGS in phase 1. Another possible explanation is the increased CP content in phase 1 diets containing DDGS compared with that in CON (Table 5.2). Excessive dietary CP can reduce ADFI by increasing plasma urea concentration in growing-finishing pigs (Goerl et al., 1995; Chen et al., 1999). In

addition, in this experiment, pigs were fed a corn-soybean meal diet before consuming phase 1 experimental diets. It is therefore possible that the decreased ADFI was due to less palatability of diets containing DDGS. Hastad et al. (2005) showed that when given a choice, pigs prefer to consume a corn-soybean meal diet over a diet containing DDGS. Hilbrands et al. (2013) also reported a reduction in ADFI for pigs switched from a corn and soybean meal based diet to a diet containing DDGS with low AA digestibility. Furthermore, our data suggest that the negative effect of feeding 30% DDGS on ADFI was limited in phase 1, while pigs were able to maintain adequate intake during phases 2 to 4. For the main effects of feeding DDGS, overall ADFI of pigs fed 30% DDGS (2.80 kg/d) was less ($P < 0.01$) than that of pigs fed diets with no addition of DDGS (2.88 kg/d), which has also been reported in other studies (Xu et al., 2010a; Hardman, 2013; Graham et al., 2014b). No WM × phase interaction was observed for ADFI (Figure 5.2). Adding 15% WM to diets did not affect the overall ADFI (2.82 vs. 2.85 kg/d for pigs fed diets with and without WM, respectively).

For ADG, pigs fed the 4 dietary treatments had similar overall ADG and final BW with no DDGS × WM interaction. However, there was an interaction ($P < 0.01$) between dietary DDGS and feeding phase for ADG. Pigs exhibited a lower ($P < 0.01$) ADG and ending BW in phase 1 when 30% DDGS was fed, but no differences were observed in phases 2 through 4 (Figure 5.1). This observation corresponded to the changes in ADFI, and was in agreement with the findings from Hardman (2013) and Wu (chapter 2). Likewise, the interaction of WM × phase for ADG ($P < 0.01$) followed the same pattern as that in the DDGS × phase interaction (Figure 5.2). In phase 1, pigs fed diets with addition of WM had reduced ($P < 0.05$) ADG compared with pigs fed diets without WM.

However, overall ADG was not affected by adding 30% DDGS or 15% WM to diets (Table 5.6).

Overall G:F of pigs fed the 4 dietary treatments was not different, and no interaction between DDGS and WM was observed. Pigs fed diets with or without addition of DDGS had similar G:F during phases 1 to 3, but this efficiency was improved ($P < 0.01$) in phase 4 when 30% DDGS were fed (DDGS × phase interaction; $P < 0.01$; Figure 5.1). This observation suggests that the NE value (2,114 kcal/kg as fed) used for the DDGS source fed in this study was adequately predicted when used in the formulation of phase 1 to 3 diets, but it was underestimated for pigs in phase 4. Increased gut capacity in the late finishing phase may have improved the pig's ability to digest and utilize energy from fiber through hindgut fermentation (Just et al., 1983; Noblet and Shi, 1994). Therefore, the NE value of high-fiber ingredients would be expected to increase as the BW of pigs increases. This has been confirmed by Gutierrez et al. (2014) who reported a greater NE value of a conventional high-oil (13% ether extract) DDGS source for finishing (87 to 119 kg BW) pigs compared with growing (21 to 42 kg BW) pigs (2,422 vs. 1,951 kcal/kg as-fed). The NE value of DDGS (2,114 kcal/kg) used in present experiment is within the range reported by Gutierrez et al. (2014). However, this NE value is slightly greater than that of a similar reduced-oil (5.6% EE) DDGS source measured by Wu (chapter 3; 1,924 kcal/kg), and is less than the reported value (2,343 kcal/kg for DDGS with > 6 and <9% oil) from NRC (2012). These results indicate that NE content of DDGS varies widely among sources, and dynamic estimation of NE is needed to adjust NE content based on the stage of pig growth. For the effects of feeding WM, overall G:F was not affected, and no WM × phase interaction was observed (Figure

5.2). This observation suggests that an appropriate NE estimate for WM was used in the diet formulation, assuming the NE values of corn, soybean meal, and soybean oil were accurately estimated by NRC (2012). However, the NE concentration (2,113 kcal/kg) of WM used in this study is substantially greater than other published NE values determined by Pals and Ewan (1978; 910 kcal/kg) and Stewart et al. (2013; 987 kcal/kg) using comparative slaughter experiments. Further studies are needed to evaluate the variability of NE content among WM sources.

When diets containing DDGS or WM were formulated on a similar dietary ME basis, reduction in ADG and (or) G:F was often observed when compared with pigs fed corn and soybean meal based control diets. Cromwell et al. (2011) observed a linearly decreased ADG in response to increasing dietary DDGS from 0 to 45%. Hardman (2013) also reported that overall ADG and ADFI was reduced linearly when 20 to 60% DDGS were added to diets. Likewise, Asmus et al. (2011) demonstrated that feeding 9.5 or 19% WM decreased ADG and G:F even though diets were balanced for similar ME content. Similarly, reduction in ADG and G:F were also reported by Salyer et al. (2012) when 10 or 20% WM were added to diets. In contrast, we did not observe significant treatment effects, or main effects of feeding 30% DDGS or 15% WM on overall ADG and G:F when diets were formulated on a NE basis. According to the recommended ME and NE values from NRC (2012), DDGS and WM have a markedly lower NE:ME ratio (0.68 and 0.71, respectively) than corn (0.79), indicating that the ME system is more likely to overestimate the energy value of DDGS and WM that are actually available for growth of pigs. Results from our study demonstrate that the negative effects of feeding DDGS and

WM on ADG and G:F observed in the previous studies may be diminished by using the NE basis in diet formulation.

Carcass composition

No significant interaction of DDGS × WM was observed for any carcass composition variables (Table 5.7). Hot carcass weight and carcass yield were reduced ($P < 0.01$) when pigs were fed diets with addition of 30% DDGS. Feeding 15% WM decreased ($P < 0.05$) carcass yield and tended to reduce ($P < 0.10$) HCW compared with feeding diets without WM. Other studies have reported a reduction in HCW and yield with the addition of DDGS (Agyekum et al., 2012; Hardman et al., 2013; Graham et al., 2014a,b) and WM (Salyer et al., 2012; Stewart et al., 2013) to growing finishing diets. This is likely due to a greater gut fill and increased weight of viscera relative to BW of pigs fed high-fiber diets. Just et al. (1982) reported that an increase of 0.34 kg in gut fill could be expected with every 1% increase in dietary crude fiber. In addition, feeding high-fiber diets stimulates the secretion of digestive fluids associated with fiber digestion, and is responsible for increased gastrointestinal tract and visceral organ weights that are not included in carcass yield measurement (Pond et al., 1988; Agyekum et al., 2012; Stewart et al., 2013). No treatment differences were observed for BF depth, but feeding diets containing 30% DDGS decreased ($P < 0.01$) LMA and FFL%. We suspect that pigs fed diets with addition of DDGS may not have maintained sufficient AA intake for maximal lean tissue development during early feeding phase. The ADFI of pigs fed DDGS was reduced in phase 1 when dietary and DDGS NE content were underestimated. However, the calculated SID Lys intake of pigs fed DDGS in phases 1 and 4 (17.8 and 21.4 g/d, respectively) exceeded the NRC (2012) requirements estimated for these phases

(17.1 and 17.7 g/d, respectively). Therefore, it is more likely that the use of the predicted SID coefficient (77.6%) from Almeida et al. (2013) may have slightly overestimated the digestible Lys concentration in the reduced-oil DDGS source used in this study. Prediction equations developed by Almeida et al. (2013) were based on traditional high-oil (> 9% acid hydrolyzed EE) DDGS sources. However, Curry et al. (2014) showed that SID of Lys (50.8 and 56.1%) in 2 low-oil DDGS was reduced compared with a conventional high-oil DDGS (62.2%).

In summary, results from this study show that feeding 30% DDGS or 15% WM appears to limit ADFI and ADG of pigs in early growing phases, but this effect diminishes when pigs reach a BW greater than 55 kg. Feeding diets containing high fiber content from DDGS and WM results in decreased carcass yield and HCW. Adding 30% DDGS in diets reduced LMA and FFL%, which is likely a consequence of overestimated AA digestibility for the DDGS source used. In addition, formulating diets on a NE basis minimizes the negative impact of feeding high fiber diets on overall ADG and G:F. However, to further improve the caloric and nutritional efficiency of utilizing DDGS in growing-finishing diets, NE content of DDGS sources should be dynamically estimated according to the physiological age of pigs.

Table 5.1. Analyzed nutrient composition and physical characteristics of feed ingredients (as-fed basis)

Item	DDGS[1]	Wheat middlings	Corn	Soybean meal
DM, %	89.15	88.08	87.43	88.18
CP, %	29.85	15.39	7.25	47.76
Ether extract, %	6.20	3.44	2.90	0.26
Ash, %	5.55	5.02	1.11	6.35
ADF, %	10.14	11.61	3.75	6.40
NDF, %	24.17	38.31	8.51	7.15
Ca, %	0.06	0.10	<0.01	0.34
P, %	0.81	1.03	0.18	0.58
Starch, %	5.92	22.49	61.90	0.88
Particle size, μm	340	500	-	-
Essential AA, %				
Arg	1.36	1.04	0.33	3.46
His	0.84	0.43	0.22	1.33
Ile	1.12	0.50	0.24	2.19
Leu	3.43	0.98	0.82	3.74
Lys	1.05	0.65	0.25	3.17
Met	0.67	0.23	0.17	0.68
Phe	1.34	0.62	0.33	2.41
Thr	1.20	0.51	0.27	1.89
Trp	0.21	0.20	0.05	0.67
Val	1.47	0.72	0.34	2.25
Non-essential AA, %				
Ala	2.09	0.74	0.51	2.06
Asp	1.94	1.12	0.54	5.45
Cys	0.64	0.31	0.16	0.69
Glu	4.30	2.86	1.26	8.53
Gly	1.19	0.82	0.29	2.02
Orn	0.05	0.01	0.01	0.06
Pro	2.42	0.98	0.61	2.46
Ser	1.39	0.61	0.34	2.07
Tau	0.07	0.11	0.11	0.12
Tyr	1.13	0.40	0.18	1.67
NE[2], kcal/kg	2,114	2,113	2,672	2,087

[1] Distillers dried grains with solubles.

[2] Predicted NE content of DDGS obtained using a prediction equation [NE, kcal/kg = -1,130 + (0.727 × GE) – (10.829 × NDF) + (23.861 × ether extract); DM basis] developed from unpublished data from University of Minnesota, and recommended NE values from NRC (2012) for corn, soybean meal (dehulled, solvent extracted), and wheat middlings.

Table 5.2. Diet composition, phase 1 and 2 (as-fed basis)

	Phase 1 (29 to 50 kg BW)				Phase 2 (50 to 75 kg BW)			
DDGS[1], %	0	0	30	30	0	0	30	30
WM[1], %	0	15	0	15	0	15	0	15
Ingredients, %								
Corn	72.27	58.29	47.77	33.41	74.75	64.66	54.09	39.38
Soybean meal	24.48	22.38	17.10	15.34	22.75	16.90	11.63	9.89
DDGS	-	-	30.00	30.00	-	-	30.00	30.00
WM	-	15.00	-	15.00	-	15.00	-	15.00
Limestone	1.11	1.25	1.41	1.56	0.85	0.51	0.24	-
Monocalcium P (21% P)	1.09	0.70	0.44	0.05	0.94	1.11	1.27	1.48
Salt	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
VTM premix[2]	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
L-Lys HCl	0.24	0.25	0.25	0.25	0.06	0.20	0.20	0.20
DL-Met	0.09	0.09	-	-	-	0.04	-	-
L-Thr	0.07	0.07	-	-	-	0.05	-	-
L-Trp	-	-	0.01	-	-	-	0.01	-
Soybean oil	-	1.32	2.37	3.74	-	0.88	1.91	3.40
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Calculated composition								
NE[3], kcal/kg	2,456	2,456	2,456	2,456	2,474	2,474	2,474	2,474
CP, %	17.26	17.56	20.83	21.25	16.35	15.32	18.63	19.03
Ca, %	0.69	0.69	0.69	0.69	0.58	0.58	0.58	0.63
Total P, %	0.51	0.54	0.52	0.56	0.45	0.48	0.46	0.53
STTD[4] P, %	0.32	0.32	0.32	0.32	0.27	0.27	0.27	0.30
Ca : STTD P	2.16	2.16	2.16	2.16	2.15	2.15	2.15	2.10
Total Lys, %	1.14	1.15	1.17	1.18	0.96	0.95	0.98	0.98
SID[5] AA, %								
Lys	1.01	1.01	1.01	1.01	0.83	0.83	0.83	0.83
Met	0.34	0.33	0.33	0.33	0.25	0.26	0.31	0.31
Met + Cys	0.57	0.57	0.64	0.65	0.47	0.47	0.59	0.60
Thr	0.61	0.61	0.64	0.64	0.52	0.52	0.56	0.56
Trp	0.18	0.18	0.17	0.17	0.17	0.15	0.14	0.14
Analyzed composition								
DM, %	87.76	88.00	88.72	89.06	87.27	87.47	88.34	88.98
CP, %	16.62	16.36	20.19	21.74	17.45	14.44	18.10	21.49
Ether extract, %	1.80	3.00	4.32	6.20	1.75	2.87	3.90	5.20
ADF, %	3.64	5.07	5.56	6.60	4.05	5.37	5.45	7.28
NDF, %	7.66	11.95	12.85	16.83	8.50	11.12	12.30	16.99
Ca, %	0.87	1.05	0.89	0.94	0.53	0.55	0.60	0.66
P, %	0.51	0.54	0.58	0.61	0.44	0.41	0.52	0.59
AA, %								
Lys	1.14	1.24	1.19	1.23	0.96	0.96	1.02	1.02
Thr	0.68	0.76	0.78	0.81	0.62	0.61	0.71	0.80
Trp	0.22	0.26	0.21	0.25	0.22	0.20	0.19	0.21
Met	0.30	0.36	0.37	0.39	0.27	0.36	0.37	0.40

[1] DDGS = distillers dried grains with solubles; WM = wheat middlings.

[2] VTM premix = vitamin-trace mineral premix, which provided the following nutrients per kg of diet: 8,818 IU vitamin A, 1,654 IU vitamin D_3, 33 IU vitamin E, 3.3 mg vitamin K, 5.5 mg

riboflavin, 33.1 mg niacin, 22.0 mg pantothenic acid, 0.03 mg vitamin B_{12}, 0.3 mg iodine as ethylenediamine dihydroiodide, 0.3 mg selenium as sodium selenite, 55.1 mg zinc as zinc oxide, 33.1 iron as ferrous sulfate, 5.5 mg manganese as manganous oxide, and 3.9 mg copper as copper sulfate.

[3] Calculated NE content of diets based on diet formulation; NRC (2012) recommended NE values were used for corn, soybean meal (dehulled, solvent extracted), wheat middlings, and soybean oil; NE value (2,114 kcal/kg) of DDGS was obtained using a prediction equation [NE, kcal/kg = -1,130 + (0.727 × GE) – (10.829 × NDF) + (23.861 × ether extract); DM basis] developed from unpublished data from University of Minnesota.

[4] STTD = standardized total tract digestible.

[5] SID = standardized ileal digestible. Coefficients for AA digestibility were determined by equations from Almeida et al. (2013) for DDGS, and NRC (2012) recommended coefficients were used for corn, soybean meal (dehulled, solvent extracted), and wheat middlings.

Table 5.3. Diet composition, phase 3 and 4 (as-fed basis)

	Phase 3 (75 to 100 kg BW)				Phase 4 (100 to 120 kg BW)			
DDGS[1], %	0	0	30	30	0	0	30	30
WM[1], %	0	15	0	15	0	15	0	15
Ingredients, %								
Corn	81.40	67.02	56.41	41.40	83.60	69.20	58.59	43.27
Soybean meal	16.08	14.32	9.05	7.33	14.14	12.38	7.10	5.40
DDGS	-	-	30.00	30.00	-	-	30.00	30.00
WM	-	15.00	-	15.00	-	15.00	-	15.00
Limestone	0.79	0.40	0.13	-	0.69	0.30	0.03	-
Monocalcium P (21% P)	0.89	1.03	1.19	1.47	0.81	0.95	1.11	1.48
Salt	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
VTM premix[2]	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
L-Lys HCl	0.15	0.15	0.15	0.15	0.10	0.10	0.10	0.10
DL-Met	0.01	-	-	-	-	-	-	-
L-Thr	0.03	0.04	-	-	0.01	0.02	-	-
L-Trp	-	-	0.01	-	-	-	0.01	-
Soybean oil	-	1.39	2.41	4.00	-	1.40	2.41	4.10
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Calculated composition								
NE[3], kcal/kg	2,517	2,518	2,518	2,518	2,533	2,534	2,534	2,534
CP, %	13.76	14.18	17.52	17.91	12.92	13.35	16.69	17.08
Ca, %	0.53	0.53	0.53	0.62	0.48	0.47	0.47	0.62
Total P, %	0.41	0.44	0.43	0.51	0.38	0.42	0.4	0.51
STTD[4] P, %	0.24	0.24	0.24	0.29	0.22	0.22	0.22	0.29
Ca : STTD P	2.21	2.21	2.21	2.14	2.18	2.14	2.14	2.14
Total Lys, %	0.83	0.84	0.86	0.87	0.73	0.74	0.76	0.77
SID[5] AA, %								
Lys	0.72	0.72	0.72	0.72	0.63	0.63	0.63	0.63
Met	0.22	0.21	0.30	0.29	0.20	0.20	0.29	0.29
Met + Cys	0.42	0.42	0.57	0.57	0.39	0.39	0.55	0.55
Thr	0.46	0.46	0.53	0.52	0.42	0.42	0.50	0.50
Trp	0.13	0.14	0.13	0.13	0.12	0.13	0.11	0.11
Analyzed composition								
DM, %	87.12	87.40	88.12	89.04	86.84	87.48	87.74	88.97
CP, %	14.57	14.05	18.73	18.19	14.19	12.00	17.07	17.95
Ether extract, %	1.74	2.75	4.10	5.90	1.60	2.17	4.30	5.99
ADF, %	3.87	5.11	5.69	6.58	3.69	4.78	5.17	6.53
NDF, %	8.14	12.12	13.50	15.37	7.47	11.57	12.21	15.32
Ca, %	0.58	0.60	0.68	0.71	0.26	0.67	0.24	0.43
P, %	0.51	0.45	0.49	0.52	0.28	0.46	0.43	0.52
AA, %								
Lys	0.81	0.87	0.97	0.89	0.77	0.80	0.79	0.78
Thr	0.54	0.57	0.71	0.69	0.50	0.49	0.66	0.65
Trp	0.17	0.19	0.19	0.19	0.16	0.16	0.17	0.19
Met	0.22	0.24	0.36	0.36	0.22	0.21	0.38	0.34

[1] DDGS = distillers dried grains with solubles; WM = wheat middlings.

[2] VTM premix = vitamin-trace mineral premix, which provided the following nutrients per kg of diet: 8,818 IU vitamin A, 1,654 IU vitamin D_3, 33 IU vitamin E, 3.3 mg vitamin K, 5.5 mg

riboflavin, 33.1 mg niacin, 22.0 mg pantothenic acid, 0.03 mg vitamin B_{12}, 0.3 mg iodine as ethylenediamine dihydroiodide, 0.3 mg selenium as sodium selenite, 55.1 mg zinc as zinc oxide, 33.1 iron as ferrous sulfate, 5.5 mg manganese as manganous oxide, and 3.9 mg copper as copper sulfate.

[3] Calculated NE content of diets based on diet formulation; NRC (2012) recommended NE values were used for corn, soybean meal (dehulled, solvent extracted), wheat middlings, and soybean oil; NE value (2,114 kcal/kg) of DDGS was obtained using a prediction equation [NE, kcal/kg = -1,130 + (0.727 × GE) – (10.829 × NDF) + (23.861 × ether extract); DM basis] developed from unpublished data from University of Minnesota.

[4] STTD = standardized total tract digestible.

[5] SID = standardized ileal digestible. Coefficients for AA digestibility were determined by equations from Almeida et al. (2013) for DDGS, and NRC (2012) recommended coefficients were used for corn, soybean meal (dehulled, solvent extracted), and wheat middlings.

Table 5.4. Bulk densities of diets containing distillers dried grains with solubles (DDGS) and wheat middlings (WM; as-fed basis)[1]

		Treatment			
	DDGS:	0%	0%	30%	30%
Item	WM:	0%	15%	0%	15%
Phase 1[2]		599	497	563	523
Phase 2		593	497	558	501
Phase 3		598	511	551	507
Phase 4		614	532	580	507

[1] Bulk densities represent the weight per unit volume (g/L). Samples were analyzed in triplicate.

[2] Phase 1 was 29 to 50 kg BW; phase 2 was 50 to 75 kg BW; phase 3 was 50 to 75 kg BW; and phase 4 was 50 to 75 kg BW.

Table 5.5. Effects of feeding diets containing 30% distillers dried grains with solubles (DDGS) and 15% wheat middlings (WM) on growth performance of growing-finishing pigs

	BW[2]	ADFI	ADG	G:F
Source of variation, *P*-value				
Full statistical model[1]				
DDGS × WM × phase	0.26	0.13	0.61	0.59
DDGS × WM	0.89	0.77	0.40	0.60
DDGS × phase	<0.01	0.02	<0.01	<0.01
WM × phase	0.34	0.34	<0.01	0.16
DDGS	0.18	<0.01	0.16	0.25
WM	0.76	0.26	0.52	0.43
Phase	<0.01	<0.01	<0.01	<0.01
Simplified statistical model				
DDGS × WM	-	0.86	0.49	0.49
DDGS × phase	-	0.03	<0.01	<0.01
WM × phase	-	0.34	<0.01	0.16
DDGS	-	<0.01	0.16	0.25
WM	-	0.26	0.52	0.43
Phase	-	<0.01	<0.01	<0.01

[1] Full statistical model for analysis of ADFI, ADG, and G:F included all interactions and main effects; then, DDGS × WM × phase interaction was removed to simplify the statistical model if it was not significant ($P > 0.10$).

[2] Body weights were analyzed only with full statistical model.

Table 5.6. Least-squares means of growth performance measurements of pigs fed distillers dried grains with solubles (DDGS) and wheat middlings (WM)

Trait	DDGS: / WM:	Treatment 0% / 0%	0% / 15%	30% / 0%	30% / 15%	SEM
No. of pens		12	12	12	12	
BW, kg						
Initial		29.1	29.1	29.1	29.1	1.07
Phase 1		56.1	56.4	55.2	53.8	1.19
Phase 2		79.2	78.6	79.8	81.2	1.28
Phase 3		104.1	104.4	104.1	105.3	1.35
Final		122.4	121.8	120.6	119.1	1.31
Overall ADFI, kg/d		2.89[a]	2.86[ab]	2.81[ab]	2.79[b]	0.03
Overall ADG, kg/d		1.00	1.00	0.99	0.98	0.01
Overall G:F		0.363	0.368	0.369	0.370	0.004

[ab] Means with different superscripts within a row differ ($P < 0.05$).

Table 5.7. Effects of dietary distillers dried grains with solubles (DDGS) and wheat middlings (WM) on carcass characteristics of growing-finishing pigs

Trait	Treatment				SEM	Probability, $P <$		
DDGS:	0%	0%	30%	30%		DDGS	WM	DDGS × WM
WM:	0%	15%	0%	15%				
HCW, kg	90.20[a]	89.61[a]	87.21[b]	85.85[b]	0.97	<0.01	0.08	0.48
Carcass yield, %	73.81[a]	73.35[a]	72.42[b]	72.09[b]	0.20	<0.01	0.02	0.73
Backfat depth[1], mm	19.78	19.74	20.28	19.24	0.39	0.99	0.11	0.14
LM area[1], cm^2	47.89[a]	47.81[a]	44.62[b]	45.33[b]	0.60	<0.01	0.57	0.48
Fat-free lean[1], %	53.37[a]	53.33[a]	51.73[b]	52.42[ab]	0.31	<0.01	0.23	0.19

[1] Final BW was used as covariate in the statistical analysis.

[ab] Means with different superscripts within a row differ ($P < 0.05$).

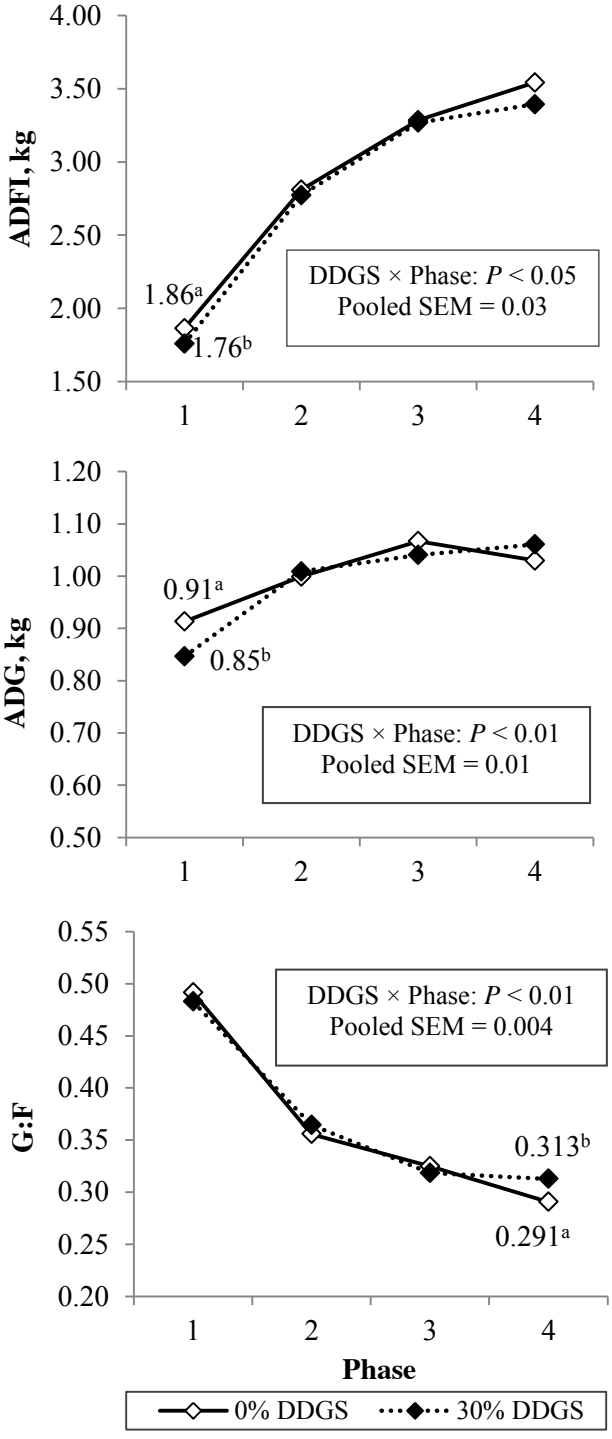

Figure 5.1. Effects of dietary dried distillers grains with solubles (DDGS) on ADG, ADFI, and G:F by growth phase. [a,b] Means within phases differ ($P < 0.05$).

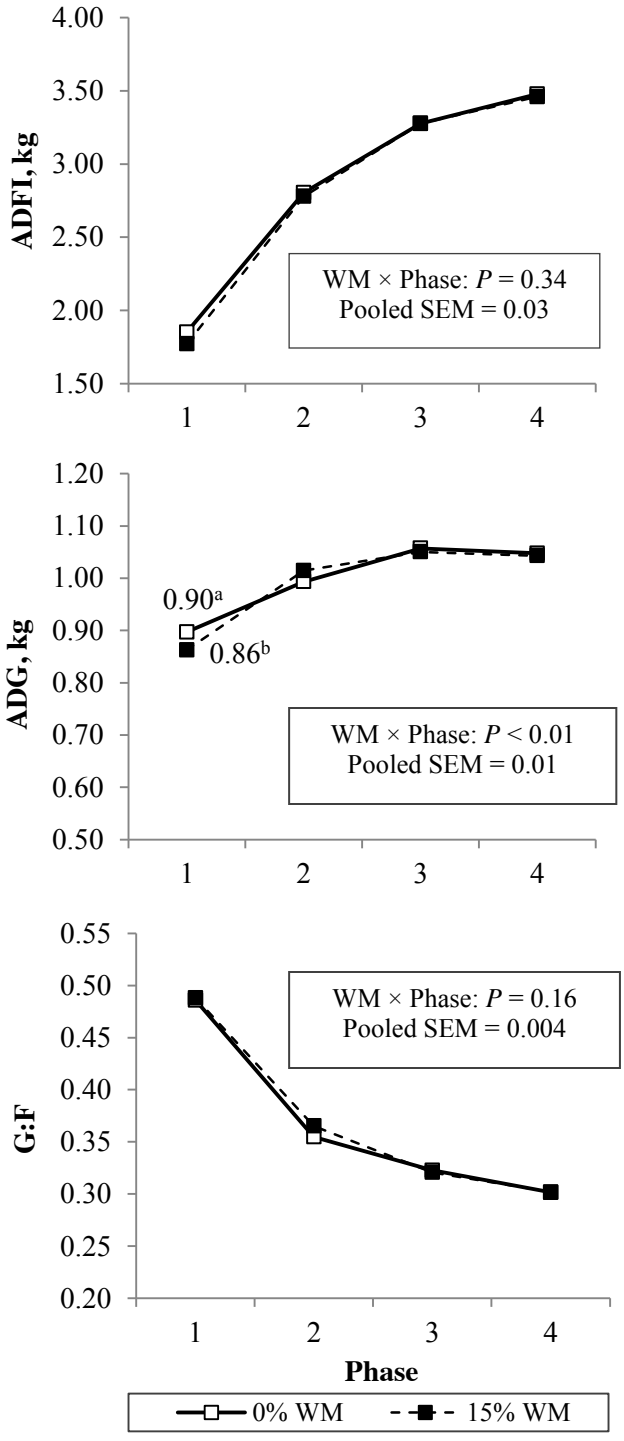

Figure 5.2. Effects of dietary wheat middlings (WM) on ADG, ADFI, and G:F by growth phase. [a,b] Means within phases differ ($P < 0.05$).

Overall summary

In swine production, feed represents the largest proportion of the total production cost, and energy represents the greatest component of feed cost. As a result, swine nutritionists and pork producers are continually focusing on finding ways to improve caloric efficiency of pork production systems. This has become particularly important in recent years due to record high prices of traditional feed ingredients, such as corn and soybean meal, leading to increased use of non-traditional ingredients such as corn distiller's dried grains with solubles (DDGS) and wheat middlings. In fact, DDGS, which is a co-product produced from dry-grind ethanol production, has been extensively used in U.S. swine diets to reduce feed cost. However, nutritionists are experiencing tremendous challenges when attempting to use accurate nutrient and energy loading values for DDGS in the diet formulation, because the inconsistent chemical composition and nutrient digestibility has caused large variability in ME and NE content among DDGS sources. The primary reason for increased variability in ME, NE, and nutrient content among DDGS sources has been due to the implementation of oil extraction by most ethanol plants. Partial oil extraction from this stillage has led to the assumption that ME and NE content of DDGS is reduced, and as a result, its feeding value is reduced. One approach to manage variability in chemical composition and energy content of DDGS is to use analyzed chemical composition and prediction equations to estimate ME and NE content of specific DDGS sources, but the precision and accuracy of these prediction equations have not been evaluated using growth performance studies.

In addition, feeding diets containing traditional high-oil DDGS sources has consistently resulted in reduced carcass pork fat quality. Pork fat quality has been commonly characterized by an increase in carcass fat iodine value (IV), and has been a

major concern when including high levels of DDGS in growing-finishing diets. In order to achieve acceptable pork fat quality when feeding DDGS diets, IV prediction equations based on the concentration and composition of dietary lipid have been developed but require evaluation for their accuracy and precision.

Feeding high-fiber ingredients such as DDGS and wheat middlings (WM) often results in reduced pig growth and carcass responses, which appear to be a result of suboptimal feed intake and overestimation of the actual dietary energy available to growing-finishing pigs when using ME as the basis in diet formulation. The research described in this thesis addressed the effects of feeding DDGS sources with variable oil and energy content, as well as the effects of increasing dietary fiber, on growth performance, carcass composition, and pork fat quality of growing-finishing pigs. Furthermore, the precision and accuracy of ME and NE prediction equations for DDGS sources, as well as equations for predicting carcass fat IV were evaluated.

Results in Chapter 2 suggested that pigs fed DDGS with variable oil concentration, but similar ME content, had similar growth performance and carcass characteristics. Reduction in oil content of DDGS improved pork fat quality by reducing IV of carcass fat depots. Using ILLUMINATE® estimates or equations developed by Anderson et al. (2012): DE = -2,161 + (1.39 × GE) – (20.7 × NDF) – (49.3 × EE) and ME = -261 + (1.05 × DE) – (7.89 × CP) + (2.47 × NDF) – (4.99 × EE) accurately predicted ME content of DDGS with medium and high oil content, but these models slightly overestimated the ME value of reduced-oil (< 6%) DDGS.

Results in Chapter 3 showed that ADFI was increased, ADG and G:F were decreased, but carcass traits were unaffected when pigs were fed DDGS sources with less

NE content. Using ILLUMINATE® estimates and equations 4 and 5 from Noblet et al. (1994b) resulted in relatively precise and accurate NE estimates for DDGS sources.

Chapter 4 described an evaluation of various equations to predict IV of pork carcass fat depots when DDGS is included in diets for growing-finishing pigs. Although feeding diets containing 40% DDGS with low oil content generally decreased IV of carcass fat depots in pigs, oil content in DDGS is a poor single predictor of carcass fat IV. Using dietary IV product or linoleic acid concentration resulted in more accurate and precise estimation of carcass fat IV compared with using the dietary inclusion rate of DDGS. However, improved prediction could be achieved by including additional predictor variables such as dietary energy content, growth performance, and carcass composition measures.

In Chapter 5, our results showed that adding 30% DDGS or 15% WM to diets limited ADFI and ADG of pigs in early growing phase, but this effect diminished when pigs reached greater BW. In addition, DDGS had greater NE value in the late finishing phase than in the early feeding phases, which may be due to an increased ability of pigs to ferment dietary fiber with increasing physiological age. Formulating diets on a NE basis minimized the negative effects of feeding DDGS or WM on overall ADG and G:F, which has been often observed when diets were formulated on a ME basis.

In conclusion, reduced oil concentration in DDGS has minimal, if any effect on growth performance and carcass composition when ME content is accurately predicted. Due to inconsistent oil digestibility among DDGS sources, oil content is a poor single predictor of ME and NE values. However, the reduced oil concentration in DDGS generally improves pork fat quality when high levels of DDGS are added to growing-

finishing diets, but the magnitude of this improvement is not proportional to the change in oil content among DDGS sources. Therefore, digestibility of dietary lipid should be included in future prediction models for estimating carcass fat IV. Our results confirm those previous studies showing that ME and NE content of DDGS sources are highly variable. Accurate and precise prediction equations can be a useful tool to manage this variability, but current prediction models need to be further refined to improve the estimation of ME and NE content by accounting for the differences in digestibility of lipid, fiber, and other nutrients among DDGS sources. In addition, we have proposed a novel approach to estimate energy content of feedstuffs using the NRC (2012) growth model and observed pig growth performance (gain:feed responses). Finally, increased dietary fiber from DDGS and WM appears to limit feed intake of pigs with light BW (< 55 kg), and decreases hot carcass weight and carcass yield. To optimize caloric efficiency of pigs fed high-fiber ingredients, diets should be formulated on the NE basis, and NE value of feedstuffs should be estimated dynamically for pigs at different stages of growth.

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